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Development of Generalized Trimaran Hullform Design Methodology for a Naval Warship

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Development of Generalized Trimaran Hullform Design Methodology for a Naval Warship

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the requirements for the degree of

Master of Science
in
Naval Architecture & Marine Engineering

by

Samuel F. Kulceski

B.S. University of Maryland, 2007
M.S. University of New Orleans, 2014

May, 2014

For my Grandparents

Rose & Leonard



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Nomenclature and Abbreviations

| | |
|----------------|---------------------------------------------------------------------------|
| α | Trim Angle (Deg) |
| A | Tow Tank Sectional Area |
| AFT | Aft of Amidships |
| AP | Aft Perpendicular |
| A_X | Model Blockage Area |
| B | Beam |
| B/T | Beam to Draft Ratio |
| C_B | Block Coefficient |
| C_{FM} | Model Frictional Resistance Coefficient |
| CH | Centerhull |
| $CISD$ | Center for Innovation in Ship Design |
| C_R | Residuary Resistance Coefficient |
| C_{TM} | Model Total Resistance Coefficient |
| Fr | Froude Number |
| Fr_n | Length Froude Number |
| FP | Forward Perpendicular |
| FWD | Forward of Amidships |
| GM^* | Metacentric Height in Relation to Waterline |
| K^2 | Sectional Area Scaling Value |
| KM | Distance from Keel to Metacenter |
| λ | Linear Scaling Factor |
| L | Length (Equal to Wetted Surface Length and Length Between Perpendiculars) |
| L/B | Length to Beam Ratio |
| LCB | Longitudinal Center of Buoyancy |
| LCS | Littoral Combat Ship |
| LPP | Length Between Perpendiculars |
| L_{VZ} | Length Between Forward and Aft Heave Potentiometers |
| ν | Kinematic Viscosity (m^2/s) |
| $NEEC$ | Naval Engineering Education Center |
| $NREIP$ | Naval Research Enterprise Internship Program |
| $NSWC$ | Naval Surface Warfare Center |
| ONR | Office of Naval Research |
| ρ | Density (kg/m^3) |
| $RHIB$ | Rigid-Hulled Inflatable Boat |
| SA | Sectional Area |
| SH | Sidehull |
| T | Draft |
| TR | Transverse Distance from Centerhull Centerline to Sidehull Centerline |
| V | Volumetric Displacement (m^3) |
| V_C | Carriage Speed (m/s) |
| $\Delta V/V_C$ | Speed Correction Due to Blockage |
| V_M | Model Speed (m/s) |
| Z_{VF} | Forward Heave |
| Z_{VA} | Aft Heave |

Abstract

The purpose of this thesis is to advance research in the development of trimaran hullforms and analyze the feasibility of the hullform for a possible naval surface combatant using current hullform design tools.

The “Generalized” Trimaran Methodology is a new process that focuses on the manipulation of the three hulled system’s total sectional area curve. The methodology is intended for rapid hull form development during the conceptual design phase, and can analyze an infinite number of trimaran hullforms.

The thesis first proposes a new methodology for the design of trimaran hullforms, describes how the process was applied to an existing hullform, presents results of the analysis, and provides validation data from a tow tank resistance experiment.

Keywords: Trimaran; Hullform Design; Sectional Area; Wave Resistance; Multi-Hull

Introduction

The purpose of this paper and the associated research project is three fold.

1. Advance research in the development of trimaran hullforms by creating a design methodology for a mathematically defined parent hull.
2. Analyze the feasibility of the trimaran hullform by applying the developed methodology in the design of a naval surface combatant with given mission requirements.
3. Utilize the current hullform design tools available to the US Navy during application process and document their functionality for multi-hull systems

Over the summer of 2013, the author participated in a Naval Research Enterprise Internship Program (NREIP) study performed by the Center for Innovation of Ship Design (CISD) at the Naval Surface Warfare Center (NSWC) in Carderock, MD to evaluate the capability of a trimaran small combatant that could fulfill Anti-Submarine Warfare (ASW), Point Defense Anti-Air Warfare (AAW), and Anti-Surface Warfare (ASuW) missions. Additionally, the study required the vessel to meet a minimum range, sustained speed, and endurance speed. The study proved the feasibility of a low risk trimaran surface combatant that meets the intended mission requirements, but identified some areas where the Navy can improve its design process in the future (Kulceski, Lister, Russell, Smith, & Sanders, 2013). One of the major short falls of the current design process is the lack of existing data for the development of trimaran warship hullforms. Meanwhile, the Navy lacks sufficient development in the tools used to design a multi-hulled warship.

In view of these needs, the present project explored the requirements of a future naval warship and determined how the trimaran hullform is well suited to fulfill many of those requirements. Additionally, the project helps further the research into the trimaran surface combatant hull design process by utilizing an “inside-out” design approach. The process focuses on minimizing the resistance characteristics of a three hulled system that meets the mission requirements of the 2013 Center for Innovation in Ship Design (CISD) trimaran small surface combatant capability study. A hullform design methodology for a “generalizable” trimaran is proposed, which has the capability of expanding the existing trimaran resistance characteristics database. This thesis documents the process and the utilization of design tools for future use in multi-hull warship designs. Finally, tow tank resistance test results are presented to validate the methodology predictions.

This project was executed under funding from the Naval Engineering Education Center (NEEC) and was sponsored by the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center in Carderock, Maryland as a continuation of a study funded by the Office of Naval Research (ONR) through the Naval Research Enterprise Internship Program (NREIP).

Background: Existing Naval Powered Trimarans

Several powered trimarans have been constructed by various navies around the world; however the application of the technology for naval warships is still in its infancy compared to its monohull counterparts.

The research vessel Triton was built as a 0.6 scale prototype for the United Kingdom's Royal Navy (Kable Intelligence Limited). The vessel is 90 meters in length (LPP) and 22.5 meters in overall beam (L/B ratio: 4.0) with a displacement of 1,100 tonnes (Australian Customs Service, 2008), and was designed as a technology demonstrator for the Royal Navy's future surface combatant frigate requirement.



Figure 1: RV Triton

The RV Triton began sea trials in October of 2000 and completed several military operations including replenishment at sea, structural loading and seakeeping trials, helicopter landing and take-off trials, towing operations, and small boat launch and recovery. Once the trials were complete, the Triton had successfully proved that the trimaran hullform could operate with the same capabilities as an equivalent monohull (Kable Intelligence Limited). The RV Triton currently operates as a patrol vessel for the Australian Customs Service and performs patrol operations in conjunction with the Royal Australian Navy patrol boats.



Figure 2: KRI Klewang

In August of 2012, the Indonesian Navy launched the KRI Klewang. The trimaran stealth patrol vessel which is 63 meters in overall length and 16 meters in overall beam (L/B ratio: 3.94) with a displacement of 219 tonnes, was intended to patrol the coastline of the Indonesian Archipelago. Unfortunately, three weeks after its launch, a spark caused a fire on board. Due to the carbon fiber construction of the hull, the vessel was destroyed by fire prior to proving its capabilities in sea trials (Eshel, 2012).



Figure 3: North Rescue 143

The North Rescue 143 small rescue vessel, which doubled as a research vessel, was constructed by China and underwent sea trials in 2011. Very little validated information was found concerning this vessel, though it is rumored that this program was recently cancelled.



Figure 4: LCS-2

The Independence Class of US Navy Littoral Combatant Ships (LCS) trimaran hulls are based on an existing high speed ferry hullform. At the time of this report, the US Navy has two commissioned vessel (LCS-2 & LCS-4) and several more planned for construction. These vessels are intended to be smaller and faster than current and future US Navy destroyers and are designed to accommodate modular mission packages for quick reconfigurations based on its next mission (Congressional Budget Office, 2003). The LCS-2 was constructed to an overall length of 127.4 meters, an overall beam of 31.6 meters (L/B ratio: 4.032), a displacement of 3,104 tonnes, and utilizes an aluminum hull.

While navies around the world are beginning to invest in advancing research in trimaran technology, the hullform has yet to be proven at the same level as the monohull. Additionally, these nations do not have mature methodologies for developing trimaran hullforms.

Naval Warship Design Requirements

The requirements of naval warships have greatly transformed from the early Cold War cruisers and destroyers and will continue to transform over the foreseeable future. The combination of the rapid advancement of military technologies, the need to perform a diverse range of missions, and the increasingly scrutinized congressional budgets has altered the roles of each surface combatant class in the fleet. The design of the future classes of ships will need to be designed to reduce life cycle costs, increase the ease of maintenance, and increase the ability to modernization the ship several times over its life.

The typical naval warship service life is intended to be 30-35 years, while the last ship of a specific class will be decommissioned 60-75 years after the start of concept design; therefore, a hull constructed today will outlive multiple generations of military mission technologies before it's scrapped. Currently, the military mission technologies are advancing so rapidly that it is difficult for the Navy to predict the specific needs of a surface combatant over the next 60-75 years. In fact, roughly 23-30 years ago cruisers and destroyers mainly carried defensive weapons and were used only to screen higher-value ships (Congressional Budget Office, 2003). Due to this unpredictability, the following requirements are essential to the future naval warships (VADM Sullivan, 2014).

- Flexibility
- Modularity
- Adaptability
- Commonality
- Scalability
- Maintainability

For a naval warship to be combat effective over its intended life, all of the ships systems and sub systems must meet these requirements, including the platform that impacts the entire ships design: the hull. To design a hull for the above "ilities", several issues must be addressed during the conceptual design phase.

- Must be designed with flexibility of installed systems in mind.
- Must be capable of accepting new technologies developed in the future (i.e. flexible infrastructure, module access routes, module stations).
- Must be designed for hull commonality, since this directly impacts the cost of a series of ships.
- Must optimize hullform with fuel consumption of the operating profile in mind.

In addition to the above "musts" the design process of naval warships would benefit in building a repository to aid programs in making cost effective acquisition and systems engineering decisions (Sumrean, 2014). Therefore, a systematic process that could produce a database of hulls, whose form could be designed to meet the listed "ilities" and whose resistance and stability characteristics are easily predicted through a set and validated methodology would be of great use. This process would provide the designers with an additional tool to gain knowledge of the capability of trimaran hullforms for warship missions, and would improve the accuracy of the cost estimating process in the conceptual design phase.

The Trimaran Hullform

Many benefits of the trimaran place the hullform in a unique position to excel as a viable option to satisfy the requirements of future naval warship designs.

The added overall beam of the three hulled system provides several benefits over a monohull, including improved transverse stability, a smaller heel angle when turning, and a large weather deck that can be utilized for a variety of deck operations. Additionally, the cross-structure provides a large arrangeable space below the weather deck while properly positioned sidehulls could protect machinery and other critical systems located in the centerhull from incoming attacks.

The centerhull of the trimaran is longer and more slender than a monohull that delivers the same payload. The additional length reduces the resistance characteristics of the vessel and improves its seakeeping, while reducing the pitch motions of the ship. With the additional length comes additional volume in the vessel, making the design driven by its weight requirement.

The aforementioned benefits can be utilized by naval ship designers to produce a flexible, adaptable, scalable, and modular warship. The large weather deck associated with the cross-structure between the three hulls allows for the ability to carry a second helicopter or additional small crafts, such as RHIBs or unmanned vehicles. The deck below the weather deck can be designed to span the entire beam of the cross-structure giving the ship designers more flexibility in the general arrangement of the vessel and allowing for modular access routes throughout the ship. This improves the vessels ability to adapt to several different mission types by quickly reconfiguring the mission modules.

The increased transverse stability gained from the sidehulls aids in the flexibility of the design of the superstructure, so that the radar cross section of the vessel can be minimized. The heat signature can also be reduced by relocating the turbine and diesel engine exhaust below the superstructure. This adds complexity to design, but increases stealth, which is very important to a military vessel.

One of the most effective solutions to meet the requirement of producibility of the hull is to design a hull with a parallel midbody. If the length of the parallel midbody can be maximized then the commonality and scalability can be increased while reducing the production costs. A long parallel midbody can also increase the flexibility of the interior arrangement of the vessel since the frames located within the midbody all have the same beam. The increased length and slenderness of the trimaran centerhull means the goal of a lengthy parallel midbody is easier to obtain since the change in curvature of the hull is smaller than a monohull¹. Finally, the trimaran typically has more gross volume than a monohull of similar size, which can be very beneficial to a vessel whose mission is expected to change several times over its life.

Of course the trimaran is not a perfect solution. There are several drawbacks to the hullform as well as areas that require much more research before their effect on the warships capability can be completely understood.

¹ When comparing the trimaran hullform to the monohull, it is assumed that both systems can carry the same payload.

The increased directional stability increases the force applied to the rudder which requires more surface area. The slenderness of the hull and the addition of the sidehulls results in a higher percentage of unusable volume on the ship. Stern boat launches can become difficult due to the slenderness of the centerhull, and the superstructure between the three hulls adds structural material (i.e. weight) that does not exist on a monohull. The added transverse stability can result in a “stiff” ship and the roll periods can affect the comfort of the crew.

The three hulls located within close proximity of each other create a wave interference drag that requires further analysis. The tools available for use in this project do not fully represent this drag, which means the requirement of model scale validation of the methodology is important. Additionally, the added stress due to the cross-structure requires more research since very few full scale warships have actually been constructed.

These drawbacks do not prevent the trimaran technology from being a possible hullform to meet the naval warship requirements.

The “Generalized” Trimaran Methodology

The “Generalized” Trimaran Methodology is a new process that focuses on the manipulation of the three hulled system’s total sectional area curve. The methodology is intended for rapid hull form development during the conceptual design phase, and can produce an infinite number of trimaran hullforms. In this thesis, the term “hullform” is used to refer to the underwater geometry of the three hulled system. The underwater geometry is described by various hullform representation models, such as the sectional area curve, offsets and lines plans, and the volume partitioning between the centerhull and sidehulls.

The following stages of the methodology are described in this report.

1. Hullform design via the total ship, sidehull, and centerhull sectional area curves.
2. Analysis using resistance prediction tools to select and optimize a hullform.
3. Validation of predicted results & methodology process by completing physical model resistance test experiments.

Hullform Design

During concept hull design, a simple process can be utilized to create a family of hullforms that can be easily analyzed. Therefore, the proposed methodology focuses on creating a family of trimaran hullforms defined by a fixed total sectional area curve.

The total sectional area curve is first modeled by a mathematical equation of the designer’s choosing. Nearly any representation can be applied, as long as basic operations can be performed on the equation.

For simplicity, the basis of design should be a symmetrical equation with the sidehulls centered at amidships. When considering a symmetrical sectional curve, the forward and aft perpendiculars define the equation’s x-intercepts while the maximum amplitude is located at amidships such that when the total sectional area equation is integrated along the waterline length, the result is the desired volume.

The designer selects the desired fraction of the total volume that is to be allocated to the sidehulls (typically between 5% and 10% of the total ship volume), and models its length and sectional area distribution. With a fixed total sectional area, the centerhull and sidehull curves are based on their relationship and should be defined with each other in mind. The sidehull curve can be represented by nearly any mathematical equation of the designers choosing and is not required to have the same form as the total sectional area curve. The centerhull curve is then found by subtracting the sidehull sectional area curve from the total. Changing the longitudinal location of the sidehulls affects the sectional area distribution of the centerhull.

Model resistance tests scaled to small warship sizes, using conventionally shaped centerhulls, have shown that total resistance at high speed is decreased by moving the sidehulls as far aft as possible. However, at lower speeds, the most favorable resistance results were seen when the sidehulls were placed 10% of the total length forward of amidships (Gale, Hall, & Hartley, 1996). Since a warship

operates over a range of speeds, the methodology must be capable of evaluating ships with the sidehull position optimized for the ship's operating profile.

An example of this application is shown below with Equations 1, 2 and 3 using a 4th order symmetrical polynomial. The example is just one application of the methodology and is illustrated to convey the process that was used for this thesis.

$$SA_T = ax^4 + bx^3 + cx^2 + dx + e \quad \text{Eq. 1}$$

$$V_T = \int_{AP}^{FP} ax^4 + bx^3 + cx^2 + dx + e \quad \text{Eq. 2}$$

$$\frac{d}{dx} SA_T = 0 \text{ at Amidships} \quad \text{Eq. 3}$$

When applying the 4th order polynomial example, the same coefficients of the total sectional area distribution mathematical equation were used to develop the sidehull mathematical equation. The sidehull longitudinal location is centered at amidships in this equation and the length of the sidehulls is defined by the total displacement.

$$SA_{SH} = ax^4 + bx^3 + cx^2 + dx + e - C_{SH} \quad \text{Eq. 4}$$

$$V_{SH} = \int_{AP}^{FP} ax^4 + bx^3 + cx^2 + dx + e - C_{SH} \quad \text{Eq. 5}$$

$$\frac{d}{dx} SA_{SH} = 0 \text{ at Amidships} \quad \text{Eq. 6}$$

The sidehull sectional area curve is developed by slicing a portion off of the total ship curve and simply shifting this curve in y, or "sectional area", direction. In the above equations, C_{SH} is the constant associated with the shift to meet the desired percentage of total volume.

The centerhull sectional area curve is obtained by taking the difference between the equations developed for the total ship and sidehull sectional areas.

Continuing with the 4th order polynomial example, the resulting sectional area curve relationship is shown in Figure 5.

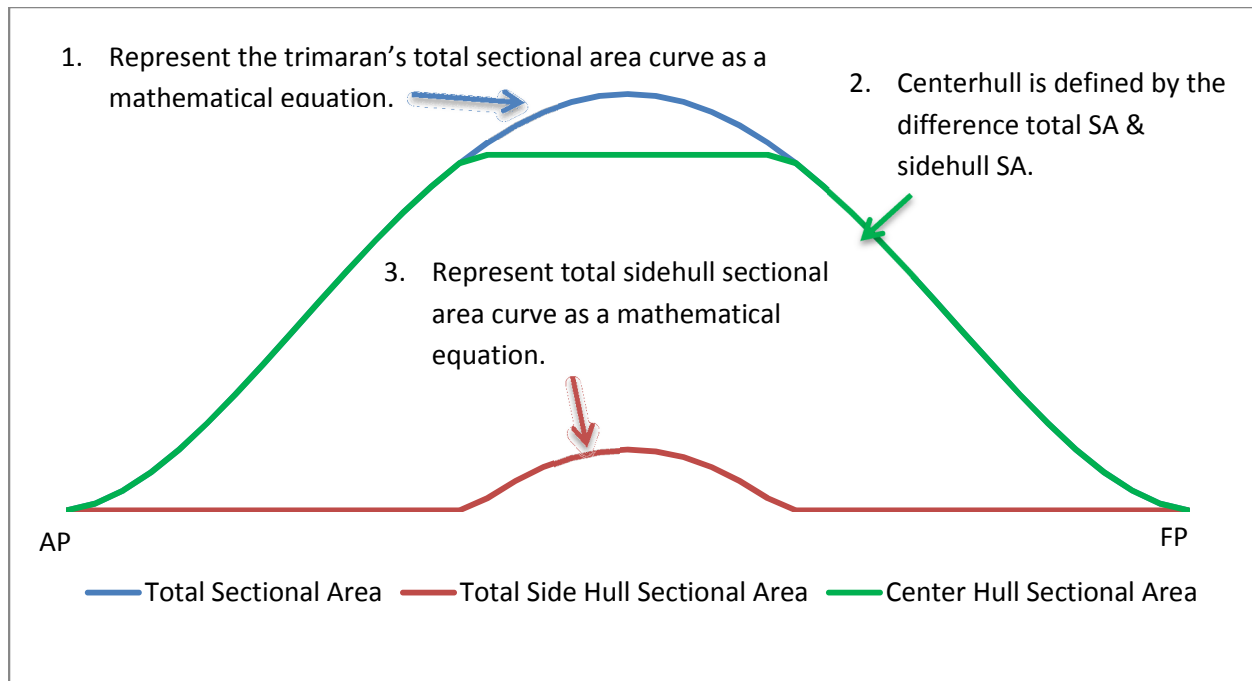


Figure 5: 4th Order Polynomial Example Sectional Area Curve

As previously mentioned, the methodology does not require the equation created for the sidehull sectional area to be the same as the total SA equation as shown in Figure 5. The same equations were used to obtain a centerhull curve with a parallel midbody with sidehulls centered at amidships in the 4th order polynomial example. Other curve representations may require a completely different sidehull sectional area curve to obtain the desired requirements of the centerhull form.

Keeping the total sectional area fixed, Figures 6 and 7 show the effect on the centerhull sectional area curve when the longitudinal location of the sidehulls are moved aft and forward of amidships.

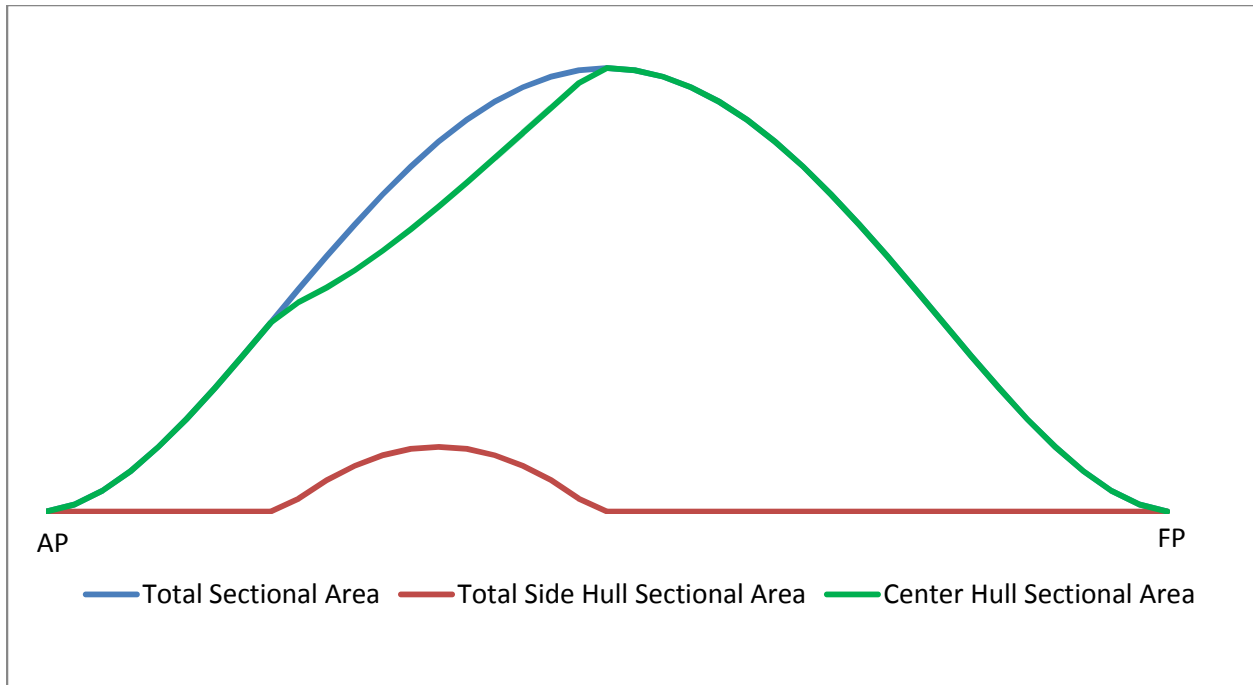


Figure 6: 4th Order Polynomial Sectional Area Curve - Side Hulls Aft

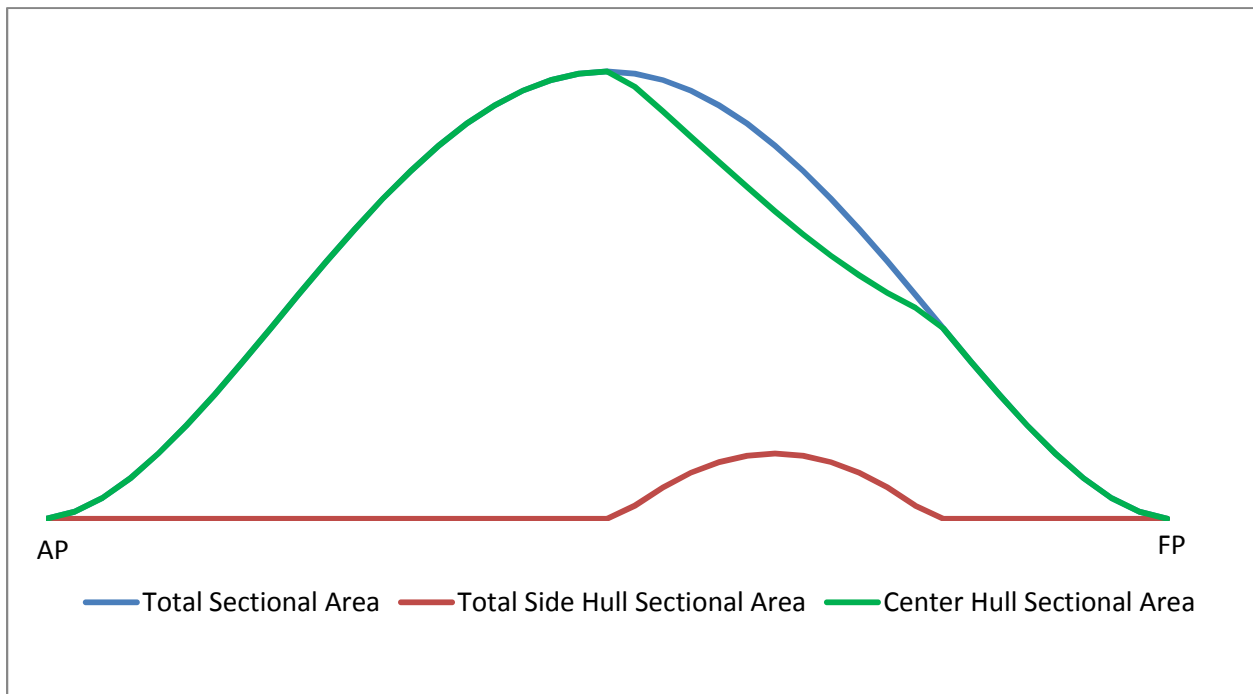


Figure 7: 4th Order Polynomial Sectional Area Curve - Side Hulls Forward

There are several advantages of designing from a fixed total sectional area curve. First, the curves are easily modified to meet a desired waterline length or to meet a desired total displaced volume. The above figures have no axis values to emphasize this point. The designer can also define sectional area requirements such as vertical launching systems or machinery spaces at specific longitudinal locations.

Parallel midbody can be designed in the centerhull. This is most evident in the 4th order example where a constant sectional area is obtained along the length of the sidehulls. When the sidehulls are moved longitudinally away from amidships, parallel midbody can be obtained only through changes in the keel curve. Once a total sectional area curve is defined by a mathematical equation, it can be easily replicated for ships with differing length, sidehull longitudinal position, total displaced volume, and sidehull displaced volume requirements. This allows the designer to analyze many variations of the design. A three dimensional hullform is then created from their respective sectional area curves and a set of scalable offsets are generated.

A major benefit of this methodology is that it can be used to create new hullforms as well as to modify existing ones. Creating a new hullform from the designed sectional area curve may be the most effective method when attempting to optimize the hullform for specific mission requirements. In some cases however, the designer may wish to analyze how an existing trimaran hullform performs under new mission requirements.

Hullform Analysis

The alternative hullforms derived from a fixed total sectional area curve needs to be analyzed based on predetermined criteria which can be accomplished by developing a matrix of hulls. Hulls with sectional area curves that correspond to several sidehull displacements and longitudinal locations can be developed for analysis. Note that although these sectional area curves are insensitive to the transverse location of the sidehulls, it is still an important factor in the hullform design. Therefore, the matrix of hulls must include several lateral sidehull positions in addition to the variations in the longitudinal location. The hull matrix is now populated with the three dimensional hullforms created from the original total sectional area curve and is analyzed using a resistance prediction tool.

Validation of Predicted Results

This process allows the designer to use many of the resistance prediction tools currently available to naval architects; however the results of the selected tool need to be validated. There are several validation methods that can be applied. The tool could replicate published tow tank experiments for similar hullforms, a comparison could be made to previously published validation results, or the predicted results could be validated against a new tow tank experiment designed for the hullform of interest. For this thesis, two of the above options were used. First, a resistance prediction tool was used to replicate the pre-existing model testing experiments. Once those results were found to be within acceptable tolerances, a model was constructed of the final hullform design developed with the methodology and tested in the University of New Orleans tow tank.

Methodology Tools

The tools described in this section were limited to those used in the 2013 CISD study. The methodology is not limited to the listed tools. If the designer is comfortable with a specific tool that can accomplish a task, it can be substituted for any of the ones listed in the document. For example, Michlet, a program based on Michell's integral, was used to predict the resistance of the generated hullforms. A Computational Fluid Dynamics (CFD) program could be used in lieu of Michlet if greater accuracy of the results was anticipated.

Microsoft Excel/Matlab

These design tools were used to create, manipulate, and analyze mathematical models of the vessels sectional area curve and hull offsets. Excel was the preferred program used. A program was written in Matlab to calculate the required length of the sidehulls and can be found in Appendix II.

Michlet/GODZILLA

Michlet is a free potential flow program that calculates the total resistance, far-field wave elevations, free-wave spectra and sea-bed pressures of thin monohulls and multihulls (Cyberaid) using an application of Michell's integral. A hull can be modeled in the program using a table of offsets, or several other available options, and the resistance of the hullform can quickly be calculated.

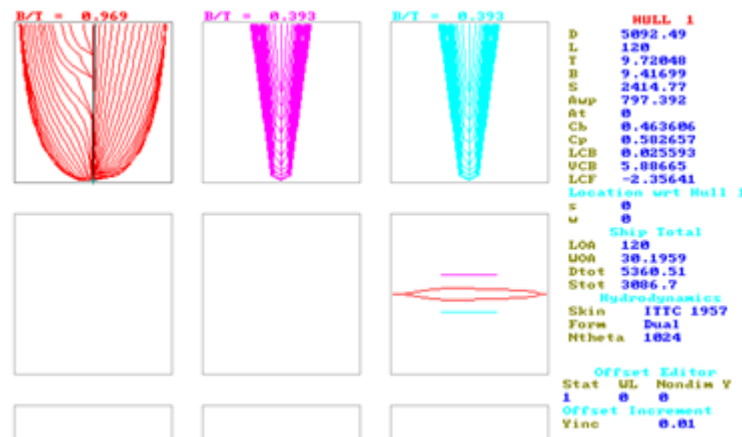


Figure 8: Michlet Home Screen

GODZILLA is the optimization module of Michlet and uses artificial life algorithms to search for hulls of minimum resistance, or for hulls of other characteristics. During the ship design process, individual vessels are selected from a population of random vessels to create new vessels. Eventually the “weaker” vessels do not survive through the generations creating the “most fit” vessel based on the imposed constraints. There are ten separate objective functions available to the user. This project’s main interest was in the minimization of the total resistance. Therefore this was the only option that was utilized.

GODZILLA can also optimize the vessel at several design speeds in which each speed can be weighted. This is useful when the vessel has a specified operating profile. The user can apply up to 26 constraints

to each hull and an additional 8 constraints to the total multihulled system. This allows the user to narrow down the design space of the optimization problem.

The optimization runs in GODZILLA take much more time than regular Michlet runs. Therefore, this process was applied to a small family of hulls that were selected from the original design matrix.

The Michlet/GODZILLA package can be useful for preliminary design of hullforms because it can provide results in a very short period of time compared to other resistance prediction programs. Since the tool is based on potential flow theory, the results are not completely accurate; therefore an acceptable design tolerance needs to be established via a validation method.

HulGen

HulGen was developed by the Naval Sea Systems Command and updated by the Center for Innovation in Ship Design (CISD) in 2011. The software is intended to be used in the early stages of ship design as a rapid hullform generation tool.

The tool can produce a body plan from a set of offsets using minimal input parameters. There are a total of 68 hullform parameters that can be adjusted to create the hullform. The user must note that the resulting body plan will not necessarily be the desired body plan since the control curves will appear mathematically smooth but are not fair in the traditional sense (Fuller, 1978). Therefore, using HulGen to recreate an exact hullform will be difficult, but the tool can be very useful to rapidly produce a large number of hullforms with differing characteristics.

Finally, the updated version of HulGen has the capability to export the necessary information to Rhinoceros to create a three dimensional model.

Rhinoceros/RhinoCAM

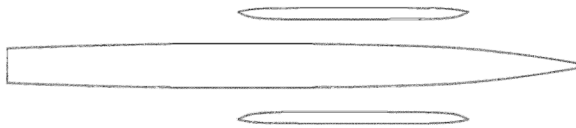
Rhinoceros can be used to create three dimensional hullforms and has the capability of fairing control curves and surfaces. RhinoCAM is an added plug-in that generates tool paths for 2 ½ to 5 axis milling and drilling robots. This program was used to create and build the trimaran model.

Tool Validation

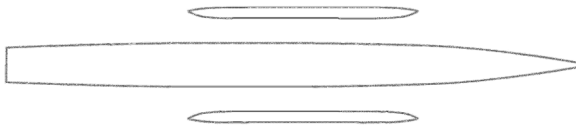
Michlet was used to predict the resistance characteristics of the hullforms developed by the methodology. Since the program is based on potential flow theory, the project required validation by comparing Michlet predictions to actual resistance test results.

Test data for a hullform similar to RV Triton (pre-Triton Model) was used to validate the Michlet trimaran resistance predictions. The pre-Triton model is a 6.0 meter model with sidehulls that was tested at five longitudinal positions. This information was used for validation because of the familiarity to the 2013 CISD study.

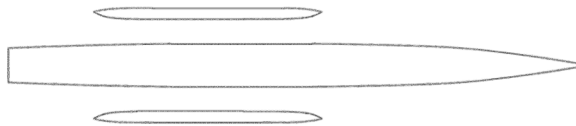
- 0.10L Fwd



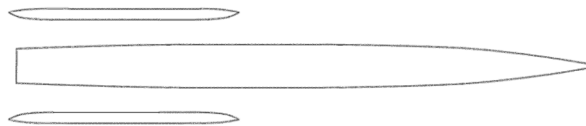
- 0.015L Fwd



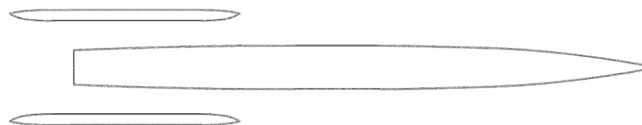
- 0.151L Aft



- 0.314 Aft



- 0.402L Aft



The resistance was measured for each longitudinal position over a speed range of 15 to 40 knots in 1 knot increments. In an attempt to improve accuracy, the sinkage versus speed curve and the trim versus speed curve from the pre-Triton test results were entered as an input to Michlet for each case.

Michlet predictions are compared with test data in Figures 9-14.

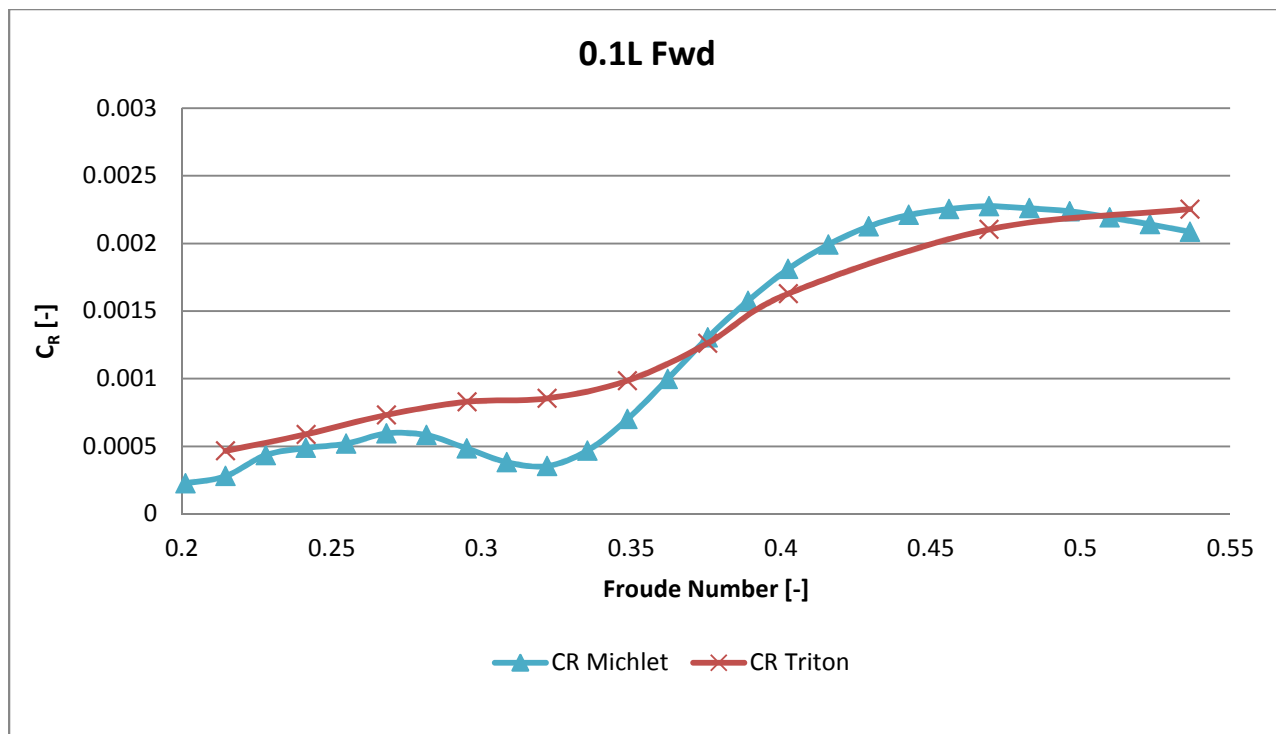


Figure 9: Michlet/Pre-Triton Comparison – Sidehulls 0.1L Fwd

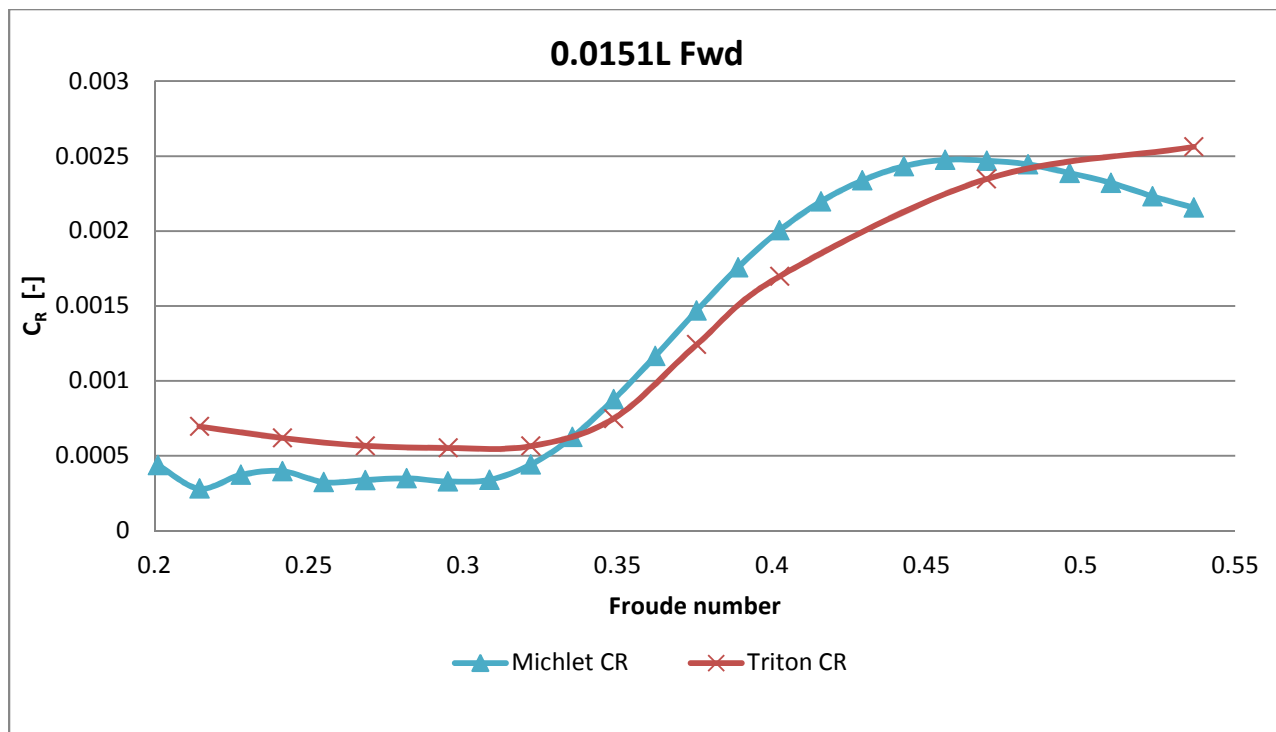


Figure 10: Michlet/Pre-Triton Comparison – Sidehulls 0.0151L Fwd

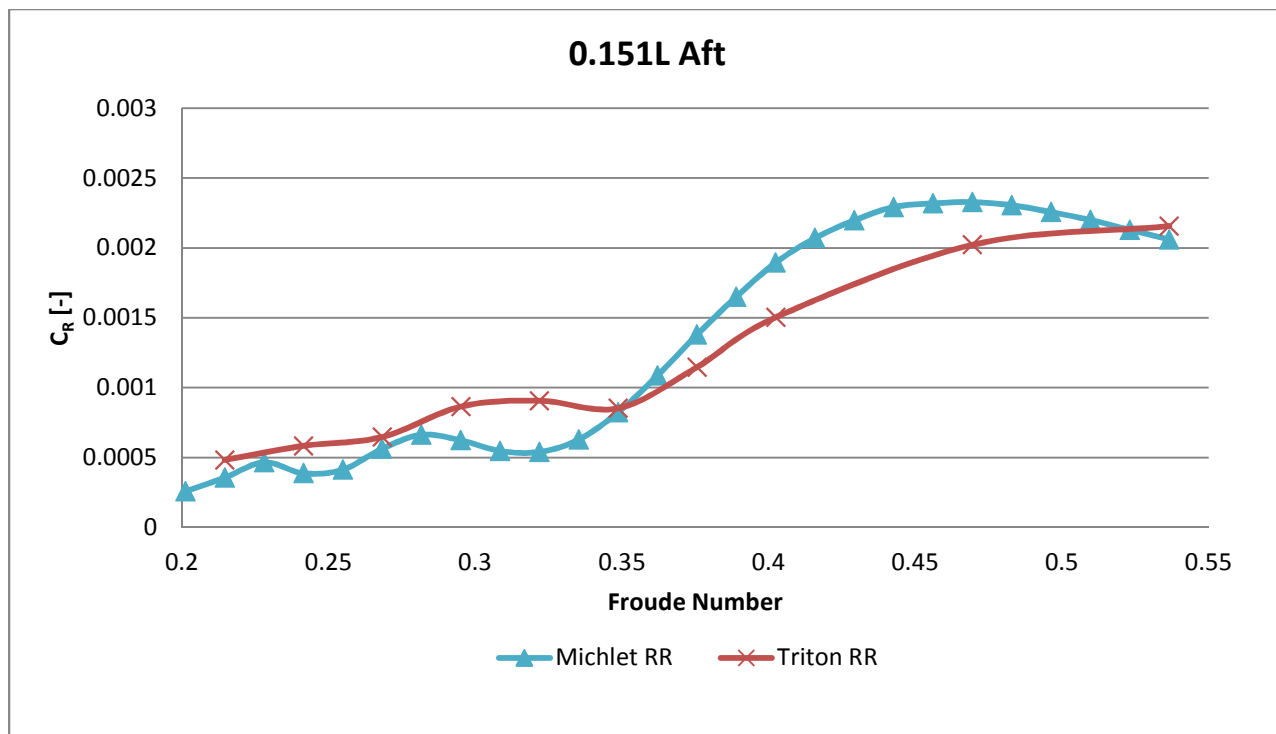


Figure 11: Michlet/Pre-Triton Comparison – Sidehulls 0.151L Aft

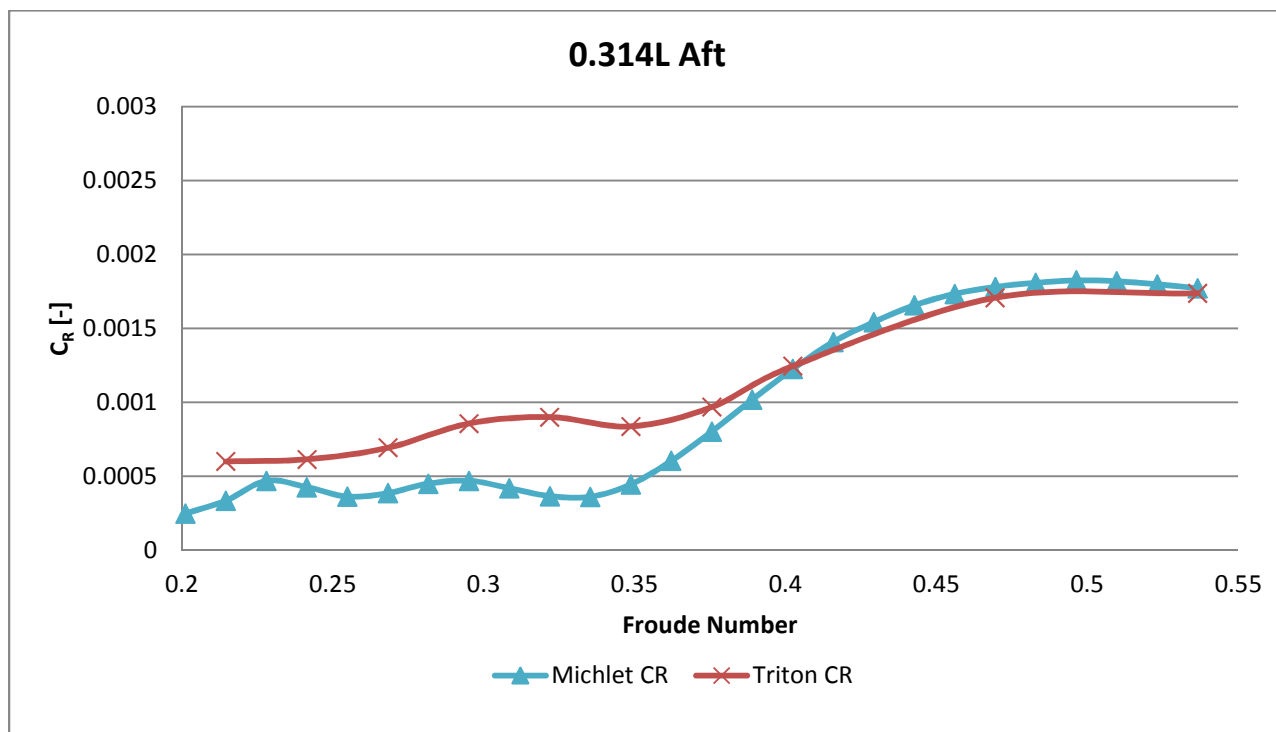


Figure 12: Michlet/Pre-Triton Comparison – Sidehulls 0.314L Aft

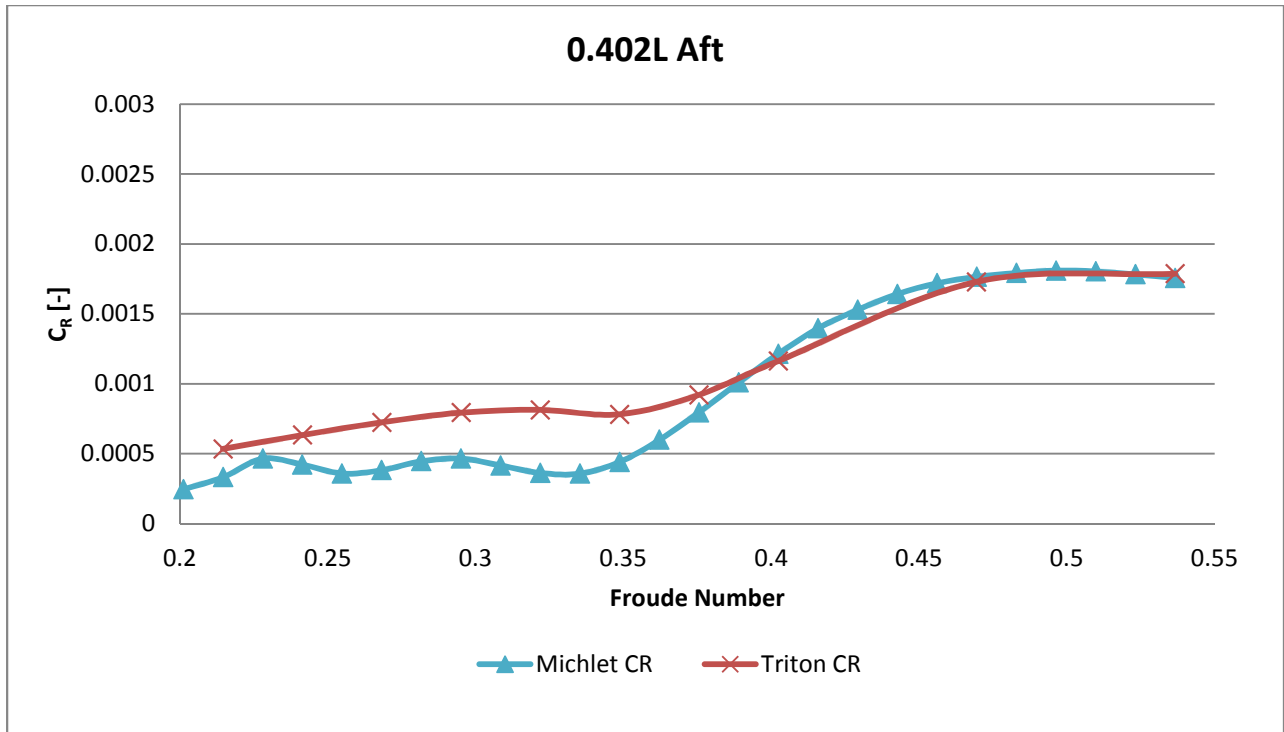


Figure 13: Michlet/Pre-Triton Comparison – Sidehulls 0.402L Aft

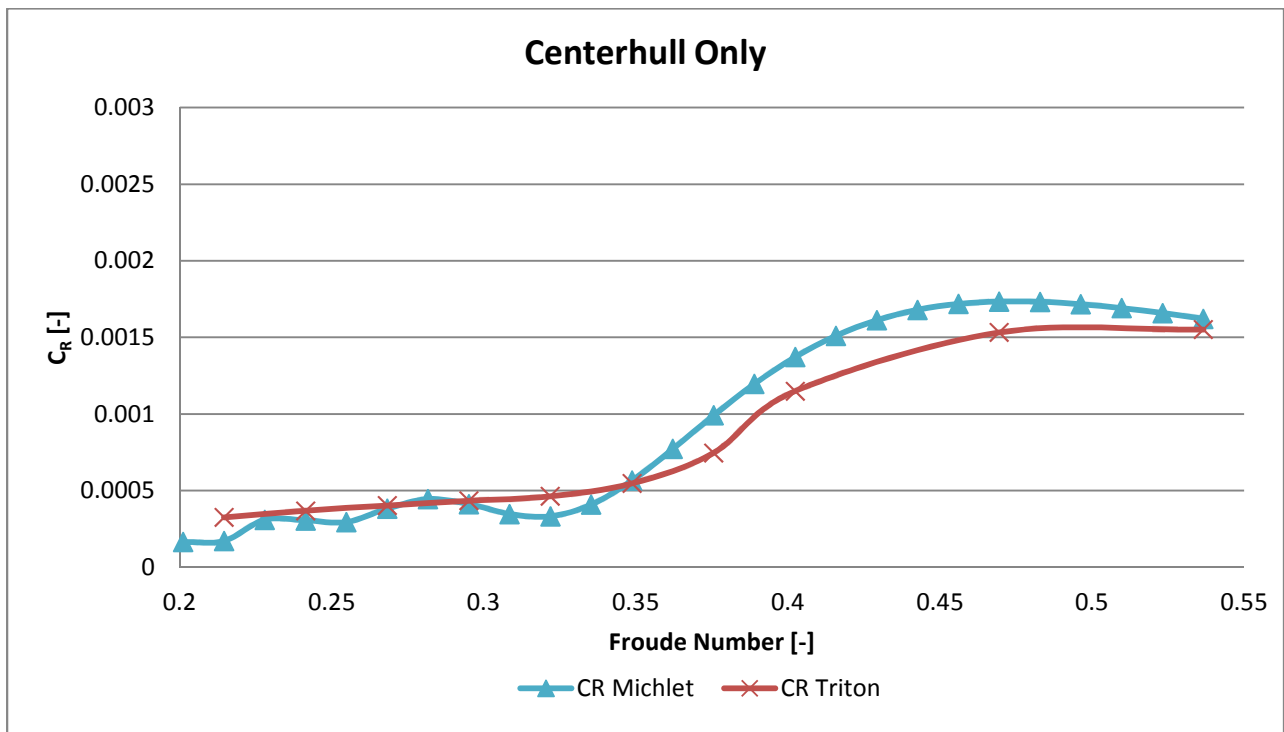


Figure 14: Michlet/Pre-Triton Comparison – Centerhull Only

Several trends appear when looking at the comparisons between the Michlet software predictions and actual pre-Triton model test data for all five longitudinal positions. The Michlet predictions have an increased presence of humps and hollows which has been well documented by many previous thin hull theory studies. At low speeds, Michlet underestimates the residuary resistance pre-Triton experimental results. While Michlet tends to over predict the residuary resistance at low speeds, there are some cases in which the opposite is true (Gotman, 2002).

Methodology Application to an Existing Trimaran Hullform

When applying the methodology to an existing trimaran hullform, the general process is still applied, however additional steps are required. The 2013 CISD study utilized the pre-Triton hullform to validate the feasibility of the trimaran hullform. The study produced a design for a surface combatant displacing 5,500 tonne that would meet the provided requirements with an imposed not to exceed length. The pre-Triton hull scaled to the calculated displacement is much longer than the imposed length constraint. Therefore, the geometry of the hullform needed adjustment so that the existing hullform could be analyzed for new mission requirements.

The original pre-Triton model is 6 meters in length and displaces 0.284 tonne (284 kg). Figure 15 displays the curves for the total ship, center hull, and the total sidehull sectional area when the sidehulls are centered at amidships.

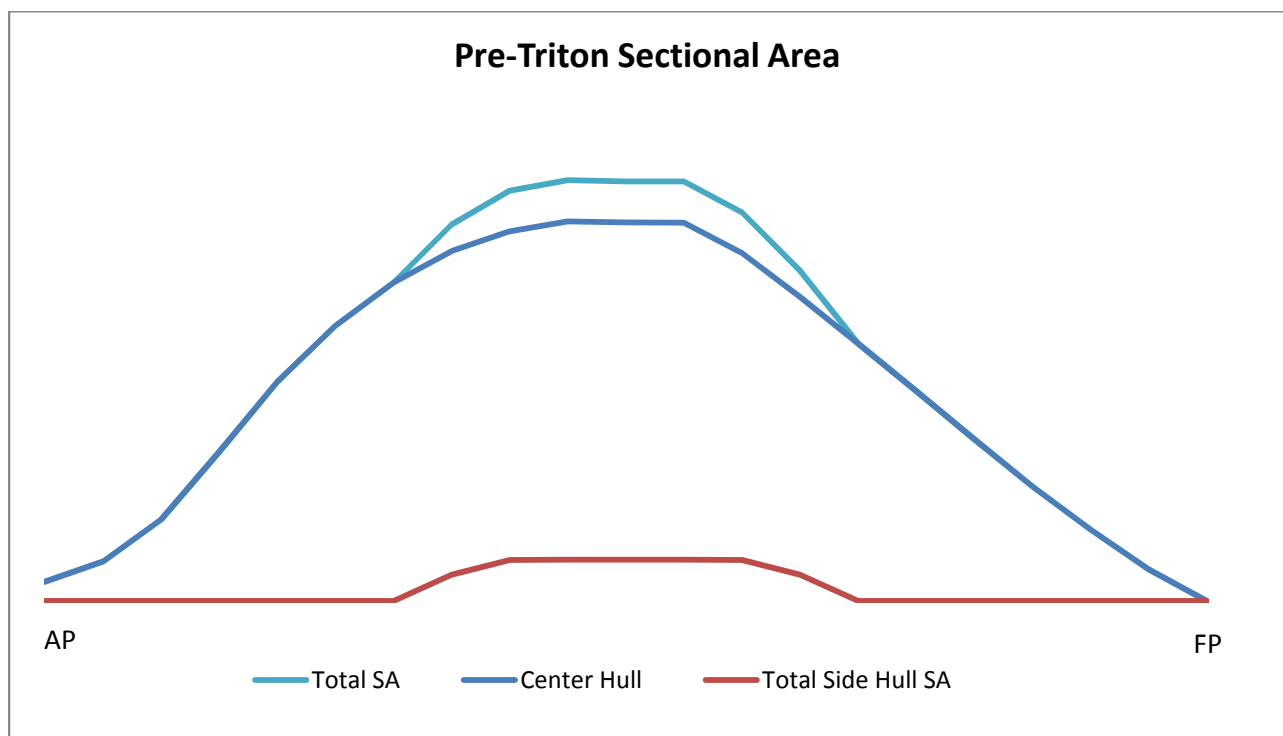


Figure 15: Pre-Triton Sectional Area Curve

The pre-Triton was designed as a 1/25th scale model of a 150 meter long, 4,437.5 tonne ship. When scaled to a vessel that meets the requirements of the CISD design, the pre-Triton had significantly less displacement (2,320 tonne) than its 5,500 tonne CISD counterpart.

First, the sectional area at each station of both the centerhull and sidehulls was calculated from the provided body plan of the pre-Triton model. The total sectional area curve resembled a symmetrical 4th order curve; therefore, a 4th order equation that closely followed the same form of the original curve was developed.

Based on the given mission, manning, and not to exceed length requirements, the CISD study developed a trimaran of 120 meters in length (LPP) with a displacement of 5,500 tonne. To meet the CISD study requirements, the following constraints were used in this project.

| | |
|-------------------------------|-------------------------------|
| Total Displacement: | 5,500 mt |
| Sidehull Displacement: | 5%, 10%, & 15% of Total Disp. |
| Length: | 120 m Maximum |
| Center Hull Beam: | 9 m Minimum |
| Center Hull Draft: | 10 m Maximum |

Table 1: Trimaran Hull Constraints

By scaling the pre-Triton length using the linear scale factor (λ) of 20 and adjusting the curves to a 5,500 tonne equivalent over a 120 length between perpendiculars, the CISD constraints of length and total displacement were met. The resulting curves can be seen in Figure 16.

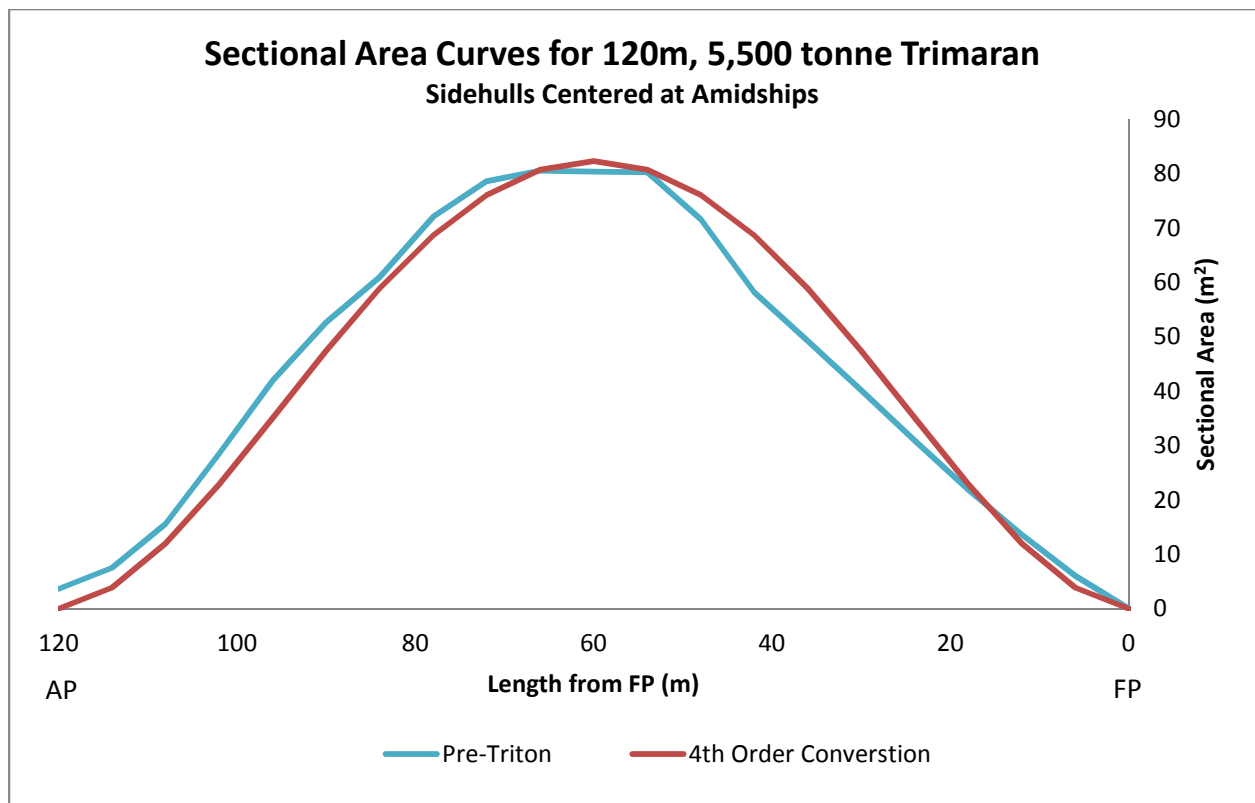


Figure 16: Pre-Triton/Generalized Sectional Area Curve Comparison

Next, both the center hull and sidehull sectional area curves were defined. The methodology was applied using the three sidehull displacements of 5, 10 and 15% of the total 5,500 tonne displacement. Using the same 4th order equation coefficients for the sidehull equations, the sectional area curves for each sidehull displacement and the resulting center hulls were produced.

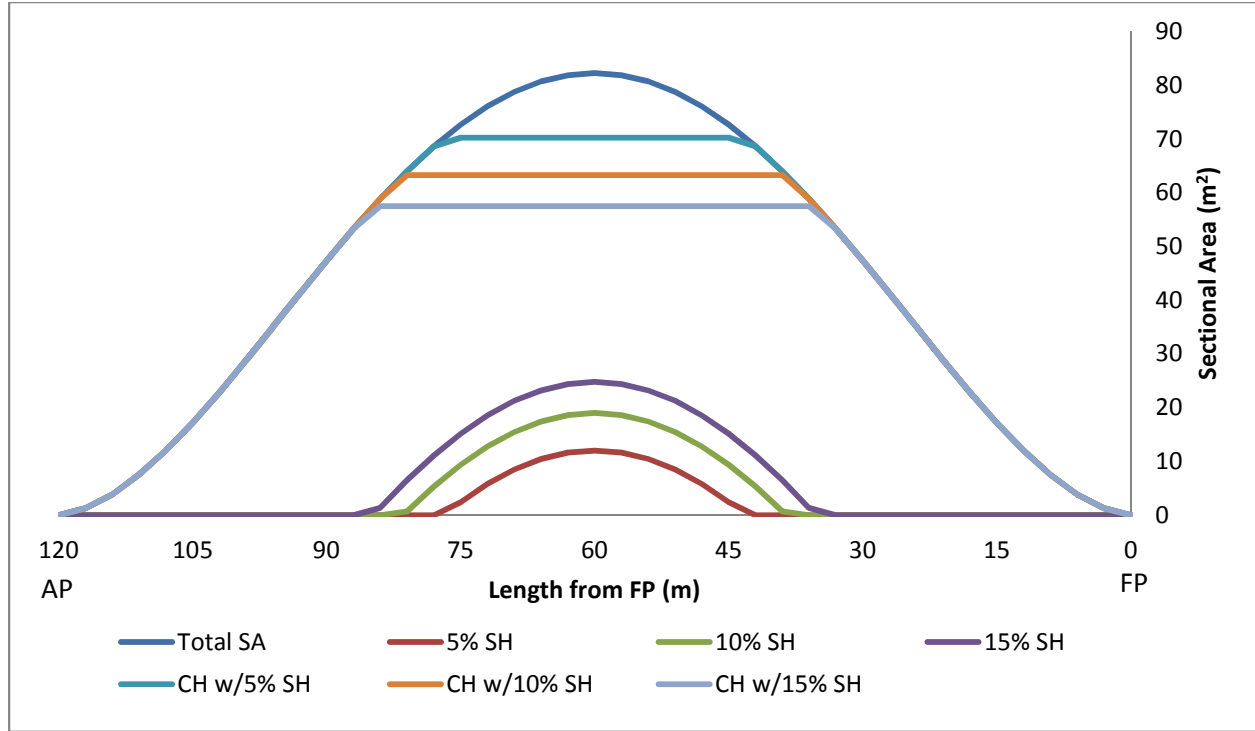


Figure 17: Generalized Trimaran Sectional Area Curves

To apply the new sectional area representation to the existing pre-Triton offsets, a scaling factor, K^2 , was introduced along the length of the hull. This factor was equal to the new trimaran's sectional area value divided by the original vessels sectional area value after length and displacement adjustments were made.

$$K_{Total}^2 = \frac{4th\ Ord\ Total\ SA}{PreTri\ Total\ SA} \quad Eq. 7$$

$$K_{CH}^2 = \frac{4th\ Ord\ Total\ SA - Total\ Side\ Hull\ SA}{PreTri\ CH\ SA} \quad Eq. 8$$

$$K_{SH}^2 = \frac{4th\ Ord\ SH\ SA}{PreTri\ SH\ SA} \quad Eq. 9$$

Note that each sectional area value represents the value for the desired hullform. Therefore the values adjusted to the 120 meter, 5,500 tonne pre-Triton vessel were used.

The main purpose of this exercise was to achieve a slender centerhull hullform with a long parallel mid body (or parallel section). The scale factor is based on area, or length squared, and when applied to the existing sectional area, the scale factor will change both the length and beam of the vessel. The K^2 value varies along the length of the center hull and effectively accomplishes the creation of a parallel midbody, but this also results in an altered and possibly “bumpy” keel curve.

To prevent this from happening, the K^2 value was applied to only the waterlines of the vessel leaving the buttocks lines untouched. This overcorrected the problem and the centerhull hullform was shaped like a coke bottle (Figure 18) since the entire sectional area factor was only being applied to the waterline.

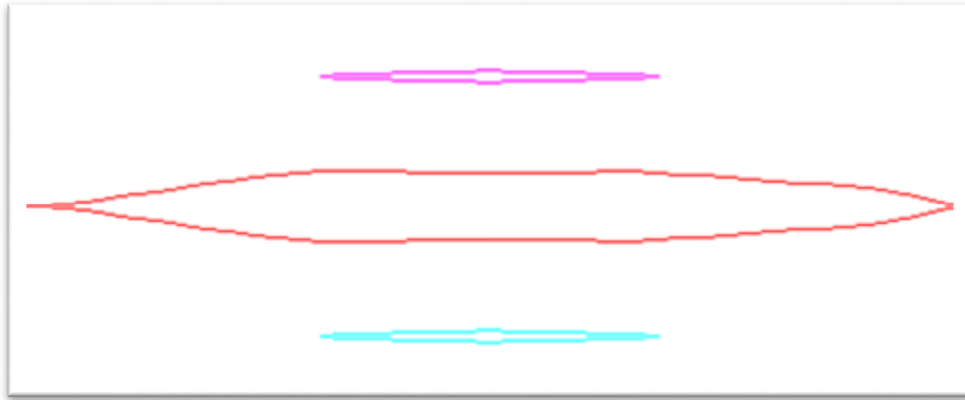


Figure 18: Coke Bottle Centerhull

The next step of the K^2 scaling method was to lengthen the sidehulls while maintaining the desired total displacement. This step created the parallel body section while maintaining the original keel curve of the vessel. The 120 meter, 5,500 tonne pre-Triton hullform's sidehull displacement ratio was very similar to the hull shown in Figure 17, but the sidehull length was nearly 15 meters longer than the 4th order equivalent. The 4th order sidehull length is defined by both the curve shape and the desired total sidehull displacement. To obtain a longer, more slender sidehull, the maximum amplitude of the 4th order sectional area curve required a reduction, while simultaneously lengthening its x-intercepts. Figure 19 displays a new center hull/sidehull relationship for the vessel previously shown in Figure 17.

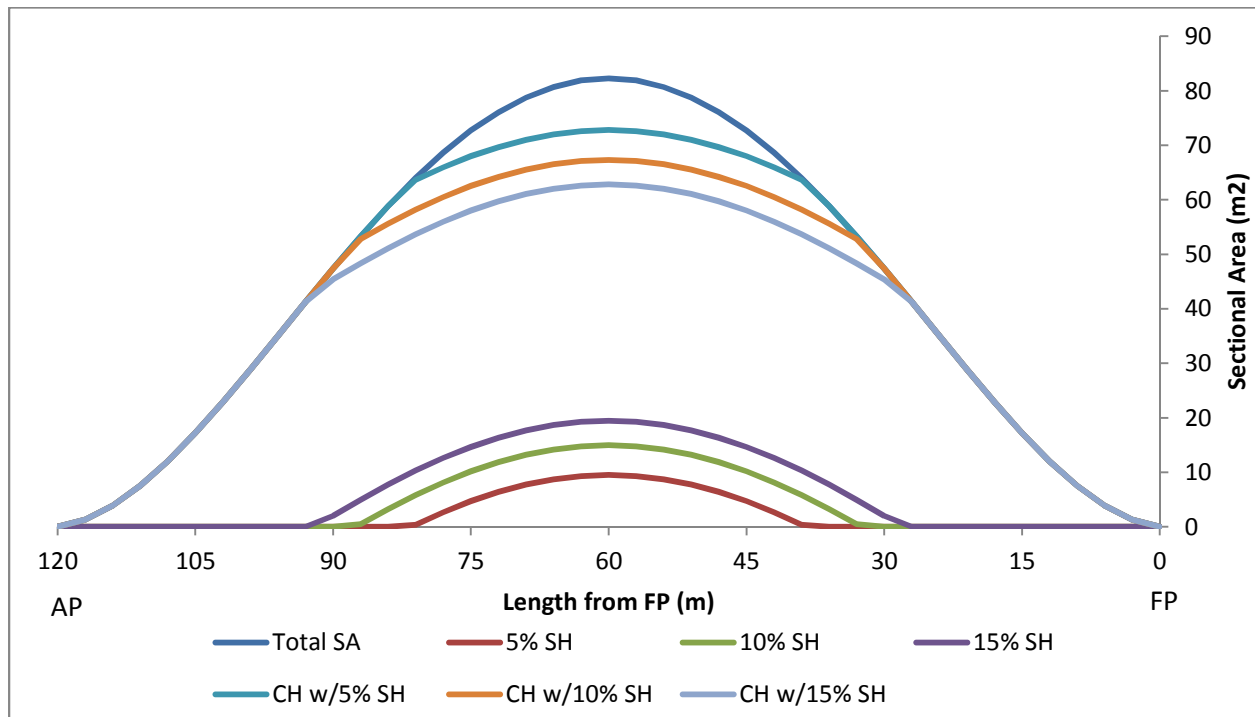


Figure 19: Sectional Area Curves w/Lengthened Sidehulls

This graph represents how the x-intercepts of the 5% total volume sidehull curve (i.e. the sidehull FP & AP) corresponded to those of the 10% total volume curve for the coke bottled vessel. Consequently, the amplitude of the same curve was halved.

Not only did this accomplish a nearly parallel midbody, but also smoothed the previously sharp corners in the sectional area curve of the associated center hulls. Figure 20 shows the resulting hull after applying the new sidehull equation.

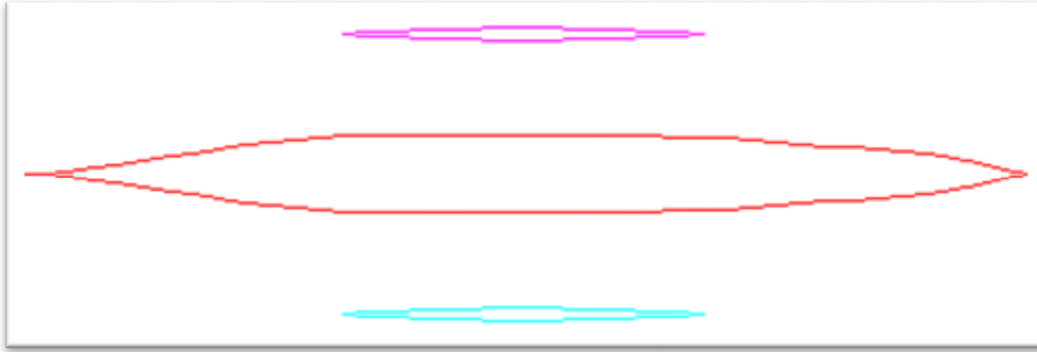


Figure 20: Trimaran with Lengthened Sidehulls - Design Waterline

The resulting hullform had been geometrically scaled by a λ of 20 and scaled by a sectional area factor applied to the centerhull beam. Since the centerhull's beam was excessive, the beam to draft ratio (B/T) was changed.

The block coefficient (C_B) was held constant to maintain the pre-Triton overall relationship. To maintain a slenderness ratio similar to the original hullform, a B/T of 1 was selected and the new beam and draft were calculated using the following equations. Note that this was not the ship's final B/T ratio, just a benchmark to produce a family of trimarans with realistic centerhulls. During the optimization process, the beam to draft ratio was optimized to meet the requirements of the hullform.

$$C_B = \frac{V_1}{L_1 B_1 T_1} = \frac{V_2}{L_1 B_2 T_2} \quad \text{Eq. 10}$$

$$\text{where } \frac{B_1}{T_1} = C_1 (\text{Known Constant}) \quad \frac{B_2}{T_2} = C_2 (\text{Desired Constant})$$

$$B_2 = B_1 \sqrt{\frac{V_2 C_2}{V_1 C_1}} \quad \text{Eq. 11}$$

$$T_2 = T_1 \sqrt{\frac{V_2 C_1}{V_1 C_2}} \quad \text{Eq. 12}$$

To validate the scaling results, the following are true:

$$\lambda_L = \frac{L_2}{L_1}, \quad \lambda_B = \frac{B_2}{B_1}, \quad \lambda_T = \frac{T_2}{T_1} \quad \text{Eq. 13, Eq. 14, Eq. 15}$$

$$\frac{V_2}{V_1} = \lambda_L \lambda_B \lambda_T \quad \text{Eq. 16}$$

These equations can be altered if the designer wishes to maintain a constant beam or draft.

The centerhull and sidehull dimensions were then set for analysis using the selected resistance prediction tool.

Now that the hullform's sectional area curve and principal dimensions have been defined, various longitudinal sidehull displacements can be analyzed. Once again, Equations 5 & 6 can be applied when shifting the sectional area curve. Figures 21 and 22 show examples of forward and aft sidehull locations.

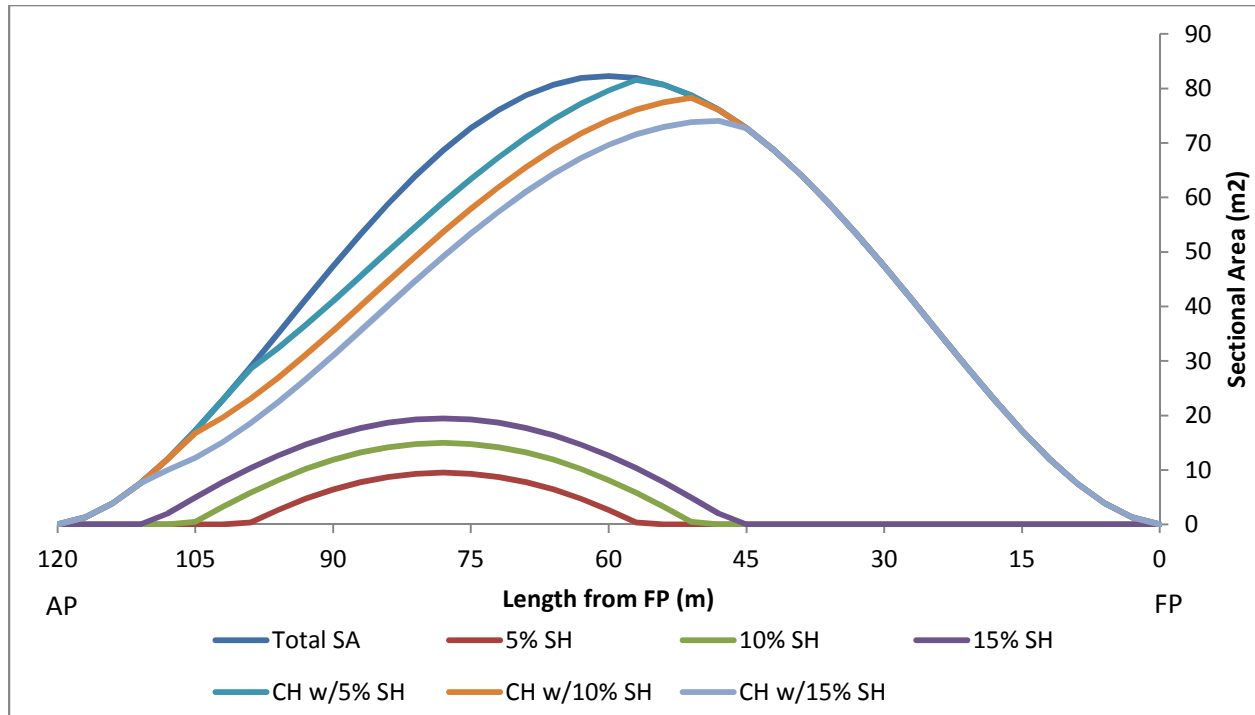


Figure 21: Trimaran with Lengthened Sidehulls Aft

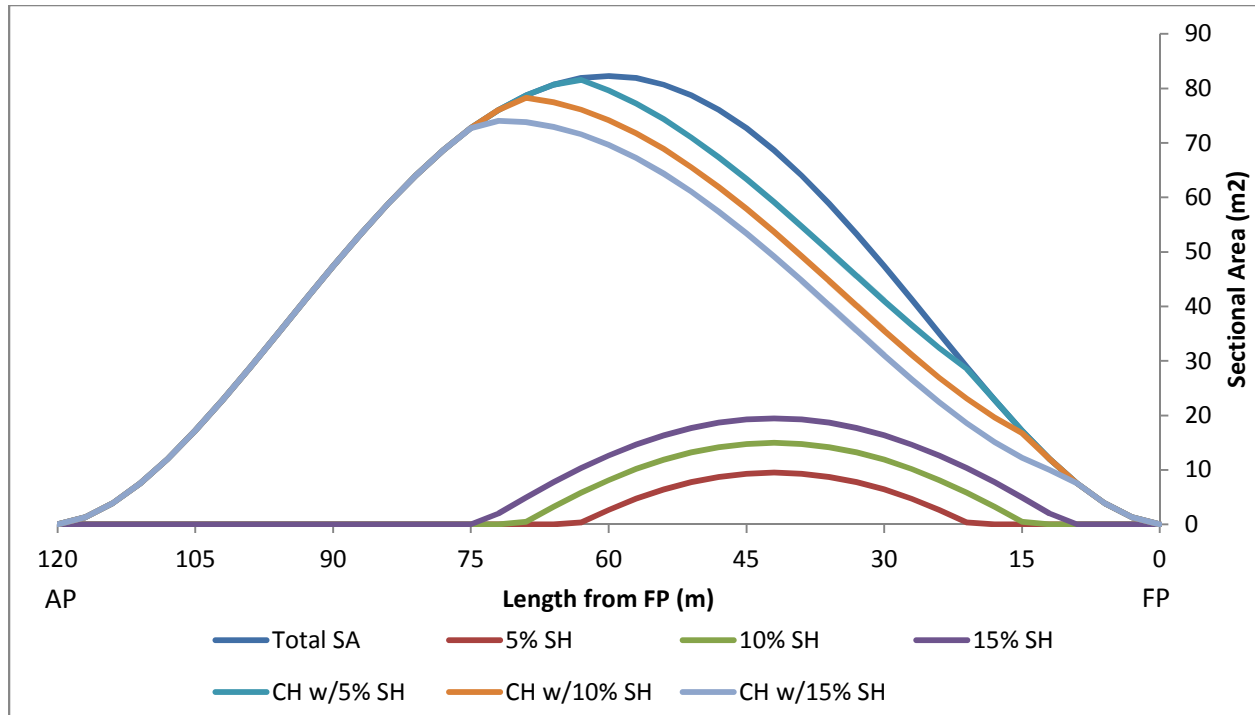


Figure 22: Trimaran with Lengthened Sidehulls Forward

Even though trimarans are typically more stable than monohulls, it's important to select an appropriate transverse location for the sidehulls.

The resistance characteristics were analyzed for the three sidehull displacements with various longitudinal locations ranging from 0.10L FWD to 0.10L AFT of amidships, at three transverse locations, and over a range of speeds from 0 – 30 knots. These results were then compared and a family of hulls was selected for the optimization process. The optimization software was used to find an “optimal” beam to draft ratio and the hull was modeled using the HulGen software. Finally, a three dimensional model was created for construction of a scale model that was later tested in the University of New Orleans School of Naval Architecture & Marine Engineering tow tank.

Hull Optimization Process

The optimization process was used to optimize for resistance while applying stability and operational profile constraints.

When analyzing a matrix of hulls using Michlet, it can be difficult to target the hullforms with adequate stability while minimizing resistance. Using the hull optimization tool GODZILLA upper and lower GM boundaries can be set. By allowing the sidehulls to be moved laterally, GODZILLA can find a transverse sidehull location that best meets its goal of minimize the resistance characteristics of the hull while providing acceptable GM.

Another useful capability that can be utilized in GODZILLA is the ability to optimize a hull for fuel consumption over a specific operating profile. The user can define several target speeds that can be weighted based on importance. The operating profile in Table 2 was used for the 120 meter, 5,500 tonne CISD trimaran design.

| Vessel Speed (knots) | % Underway |
|----------------------|------------|
| 5 | 25% |
| 15 | 40% |
| 18 | 20% |
| 22 | 10% |
| 30 | 5% |

Table 2: CISD Operating Profile

Table 2 represents the expected percentage of time that the vessel will operate at each of these speeds. These are not the weights that were used in the GODZILLA optimization software. The ships propulsion system burns fuel at differing efficiencies at each of those speeds. Therefore, the optimization process needs to consider the vessel's fuel consumption.

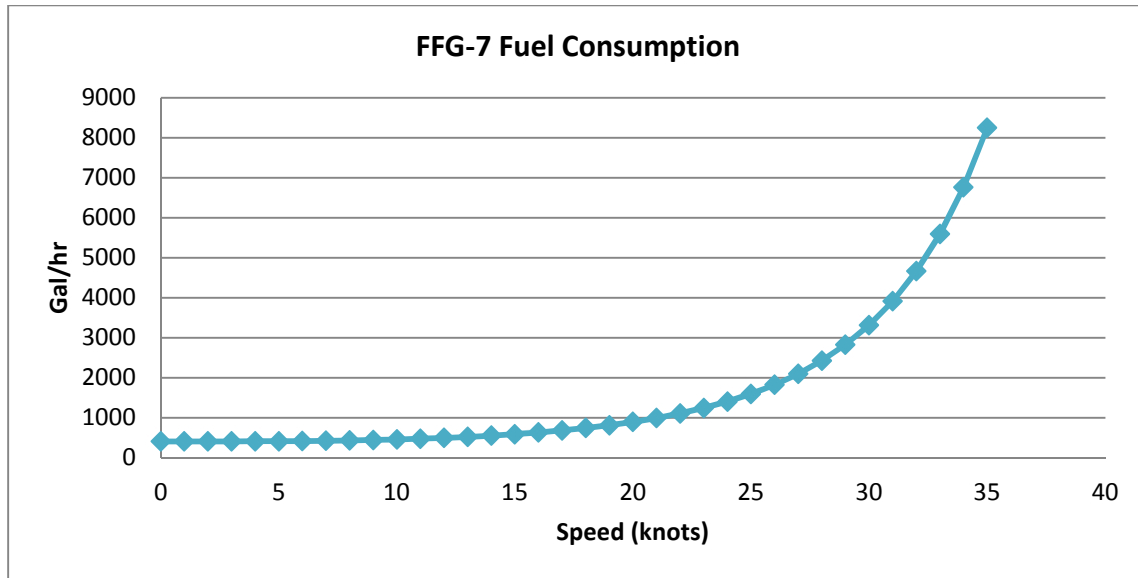


Figure 23: FFG-7 Fuel Consumption Curve

Figure 23 is data obtained from a Naval Postgraduate School (NPS) report on predicting fuel consumption of US Navy ships (Schrady, Smyth, & Vassian, 1996). The fuel consumption curve is that of the FFG-7 which has similar length, onboard power, and mission capabilities as the CISD 2013 study trimaran. To properly weigh the operating profile based on fuel consumption, the CISD operating profile was combined with the FFG fuel consumption curve and normalized. This was done by multiplying the percent time underway by the FFG consumption at each speed, then dividing by the summation of the same product over all speeds, which yielded the operating profile weighted by fuel consumption shown in Table 3.

| Vessel Speed (knots) | Weighted % Underway |
|----------------------|---------------------|
| 5 | 13% |
| 15 | 31% |
| 18 | 19% |
| 22 | 15% |
| 30 | 22% |

Table 3: Weighted Operating Profile

Consequently, the 30 knot operating point becomes the second highest rated speed when optimizing for resistance, considering the high amount of fuel burned at this condition despite only 5% of operating time.

Results

The Table 4 displays the center hull characteristics after applying the methodology and the final linear scale factors in reference to the original pre-Triton model.

| | Pre-Triton | CISD Trimaran | λ |
|------------|------------|---------------|-----------|
| Length (m) | 6 | 120 | 20 |
| Beam (m) | 0.433 | 9.64 | 22.27 |
| Draft (m) | 0.220 | 9.64 | 43.83 |

Table 4: Trimaran Centerhull Comparison

From the appropriate 4th order equation using the K^2 method, the sidehull lengths associated with each displacement are shown in Table 5.

| Sidehull Displacement (% of Total) | Length Between Perpendiculars (m) |
|------------------------------------|-----------------------------------|
| 5% | 42.86 |
| 10% | 54.96 |
| 15% | 63.98 |

Table 5: Sidehull Length Between Perpendiculars

To document multiple variations of the converted hullform and compare to a similarly scaled pre-Triton ship, a design space was developed that consisted of a matrix of hulls. Initially three sidehull displacements, three longitudinal sidehull locations, and three transverse sidehull locations for a total of 27 hulls were tested.

The original transverse location of the sidehulls centered at amidships was selected so the bow of the sidehull intersected with the line formed by the bow wave at the Kelvin angle of 19° 28' degrees. These values were used to define the lower boundary of the transverse location range.

| Sidehull Displacement (% of Total) | Transverse Location from CL (m) | Longitudinal Location from Amidships (m) |
|------------------------------------|---------------------------------|------------------------------------------|
| 5% | 12.5, 14.25, 16.5 | 0.10L FWD, MID, 0.10L AFT |
| 10% | 10.5, 13, 14.5 | 0.10L FWD, MID, 0.10L AFT |
| 15% | 9, 11, 13 | 0.10L FWD, MID, 0.10L AFT |

Table 6: Sidehull Displacements & Locations

Each variation of the ship was analyzed using the Michlet code predict resistance. This project focused on the hullform below the waterline: therefore the KG was assumed to be at the waterline. This is known to be inaccurate for an actual vessel.

The term GM^* is used in the text when referring to the stability of the analyzed hullforms and is defined as follows:

$$GM^* = KM - T \quad \text{Eq. 17}$$

GM^* is the height the metacentric height above the waterline, and acted as a set baseline on which each hullform's stability could be compared.

GM^* was recorded to ensure that the vessels being analyzed were a viable option.

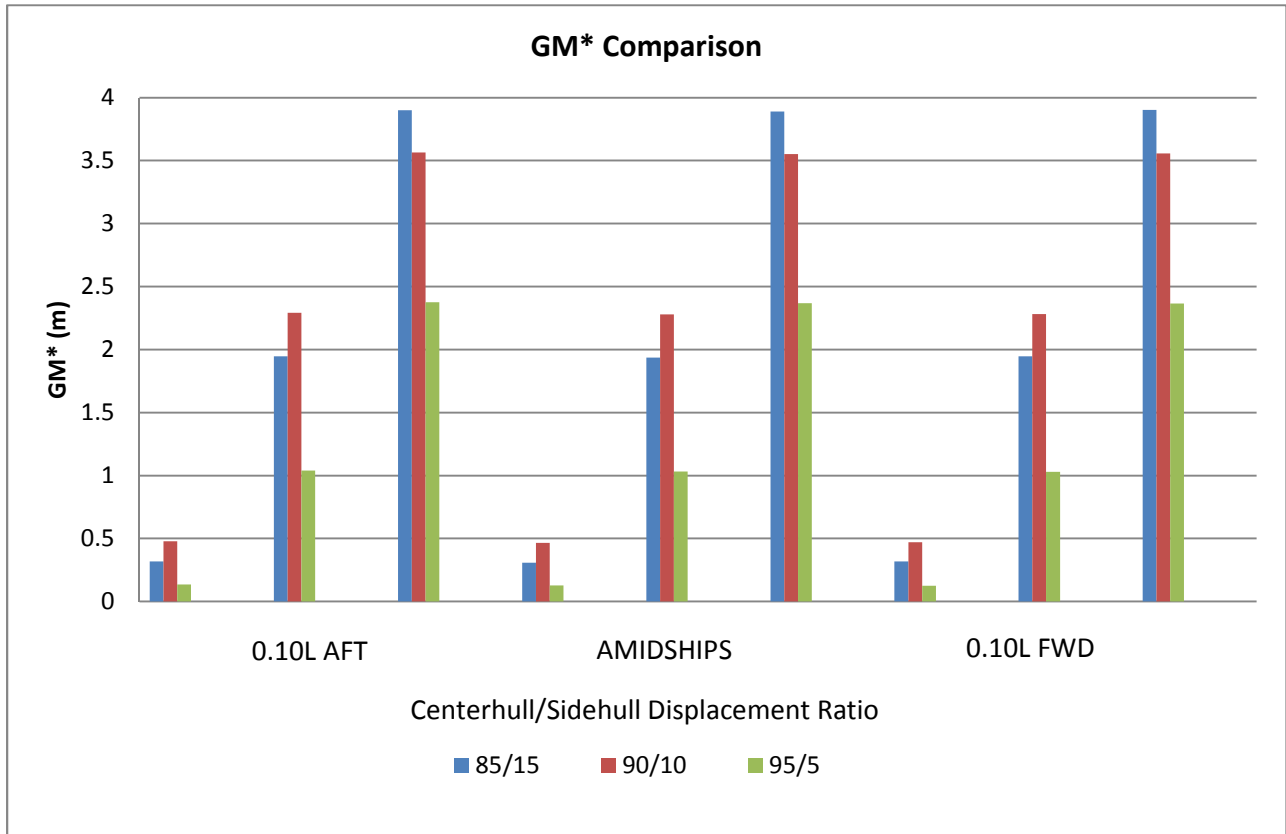


Figure 24: GM^* Comparison

To account for the known inaccuracy of GM^* , the hulls with values near zero were not considered. A GM^* constraint between 1 and 2 meters was set as the limit of the overall beam of the vessel.

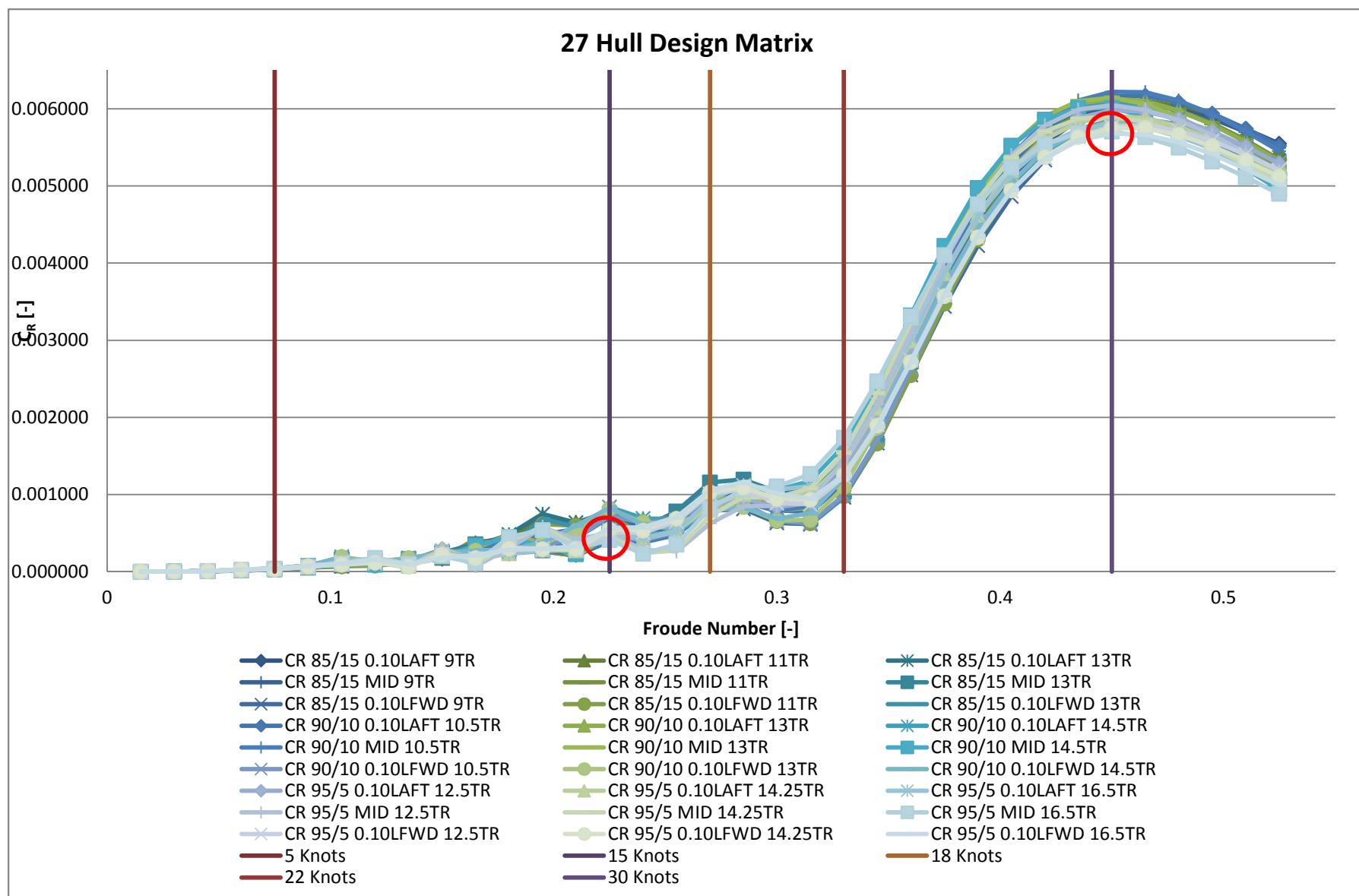


Figure 25: Hull Matrix Michlet Results

Figure 25 displays the C_R results of the design matrix evaluation. The vertical lines in the figure are the Froude numbers that correspond to the five operating speeds from the CSD operating profile. For a better understanding of the language used in the legend, see the example below.

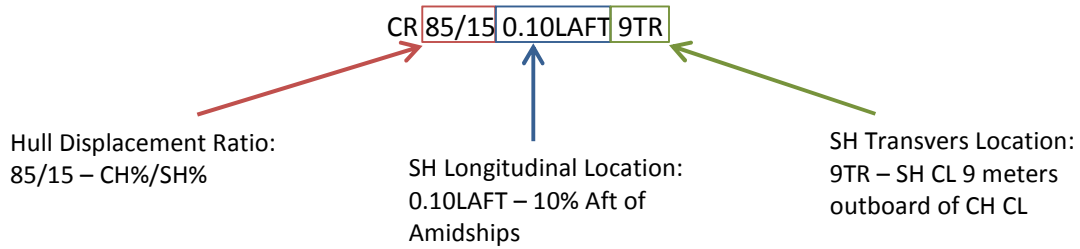


Table 7 shows the minimum, maximum, mean and standard deviation (as % of mean) of the residuary resistance coefficient at the values calculated by Michlet nearest the five operating speeds.

| Speed (Knots) | Weighted % Underway | Min C_R [-] | Associated Displacement Ratio | Max C_R [-] | Associated Displacement Ratio | Mean C_R [-] | Std Deviation (% of Mean) |
|---------------|---------------------|---------------|-------------------------------|---------------|-------------------------------|----------------|---------------------------|
| 5 | 13% | 0.027E-03 | 95/5 | 0.046E-03 | 85/15 | 0.0371E-03 | 12.62% |
| 15 | 31% | 0.393E-03 | 85/15 | 0.836E-03 | 90/10 | 0.608E-03 | 25.11% |
| 18 | 19% | 0.626E-03 | 95/5 | 1.16E-03 | 85/15 | 0.898E-03 | 13.26% |
| 22 | 15% | 0.964E-03 | 85/15 | 1.74E-03 | 95/5 | 1.29E-03 | 15.59% |
| 30 | 22% | 5.68E-03 | 95/5 | 6.22E-03 | 85/15 | 5.95E-03 | 2.66% |

Table 7: Residuary Resistance Coefficient Results

The weighted profile shown in Table 3 (pg. 28) indicates that the two speeds with the highest weighting factor were 15 (FR = 0.225) & 30 knots (Fr = 0.45). The two red circles on in Figure 25 highlight the curve with the lowest C_R at these Froude numbers. The 95/5 displacement ratio is has the lowest C_R value for the 30 knot case and had the second lowest at 15 knots. Additionally, the 95/5 displacement ratio had the majority of the minimum C_R values at all five speeds while only being responsible for one maximum value.

A family of hulls was selected for the optimization process that consisted of 95/5 displacement ratio with a GM* between 1 and 2 meters.

Figure 26 is a comparison of the three selected hulls at different longitudinal locations.

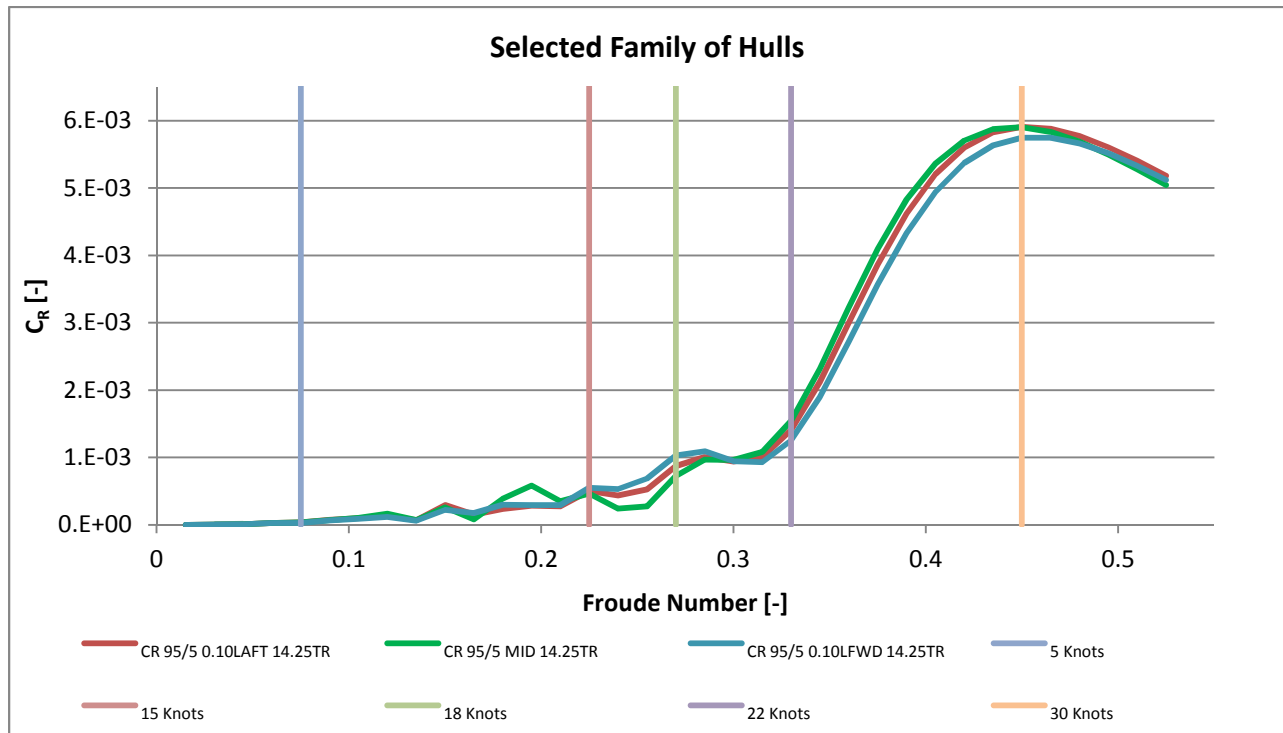


Figure 26: Selected Family of Hulls - Michlet Results

The hullform with the sidehulls centered at amidships was selected due to the nature of the sectional area curve design tool in HulGen. An argument could be made for any of the three curves in the above figure.

The selected hullform was then entered into the optimization module of Michlet, GODZILLA, and optimized to minimize resistance. This optimization process focused on optimizing the B/T ratio, and the transverse sidehull location within set constraints. The overall length, sectional area distribution, sidehull displacement, and sidehull longitudinal location were fixed. Finally, five operating speeds were weighted based on a combination of the operating profile and the FFG-7 fuel consumption curve. Predicted results for the optimized hull are shown in Figure 27. Both hulls shown in Figure 27 have the same sectional curve.

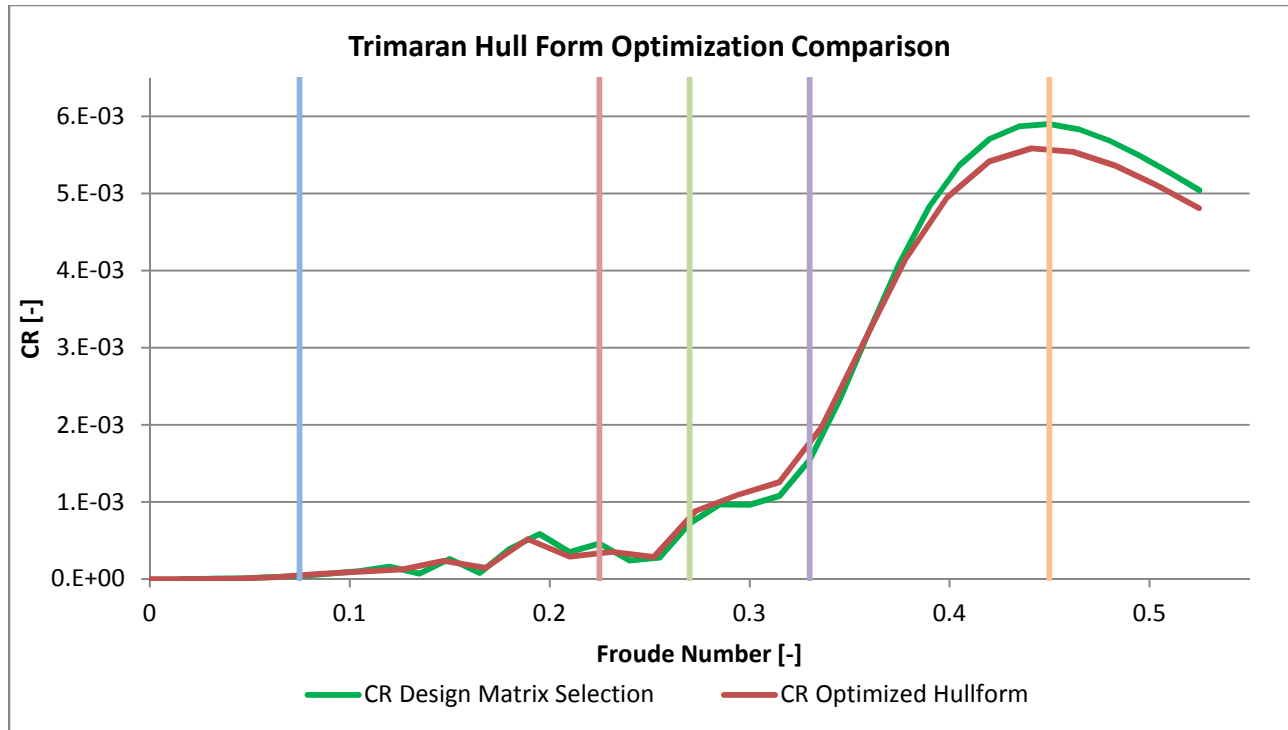


Figure 27: Optimized Hullform - Michlet Predictions

As expected the optimized hull has lower residuary resistance at the heavily weighted speeds. The centerhull and sidehull characteristics after the optimization process are shown in Table 8.

| | Centerhull | Sidehull (Each) | Total |
|-----------------------------------------------|------------|-----------------|--------|
| Length (m) | 120 | 42.865 | 120 |
| Beam (m) | 9.154 | 1.569 | 35.249 |
| Draft (m) | 9.999 | 4.660 | 9.999 |
| Displacement (tonne) | 5225 | 137.5 | 5500 |
| Block Coefficient, C_B | 0.4636 | 0.428 | [-] |
| Metacentric Height (BM_T) | -3.138 | -1.750 | 1.997 |

Table 8: Optimized Trimaran Characteristics

Up to this point, all of the results have been predicted from tools based on potential flow theory. Therefore, a testable model was required to validate the predicted results. Keeping with the stated goal to analyze the capability of the existing tools available for trimaran warship design, the program HulGen was used to create a trimaran hullform based on the optimized hullform geometry. Replicating the optimized centerhull geometry proved to be very difficult in HulGen. There are a limited number of control points; therefore, an exact representation of the sectional area curve could not be obtained. The difference between the HulGen centerhull curve and the optimized 95% centerhull curve can be seen in Figure 28.

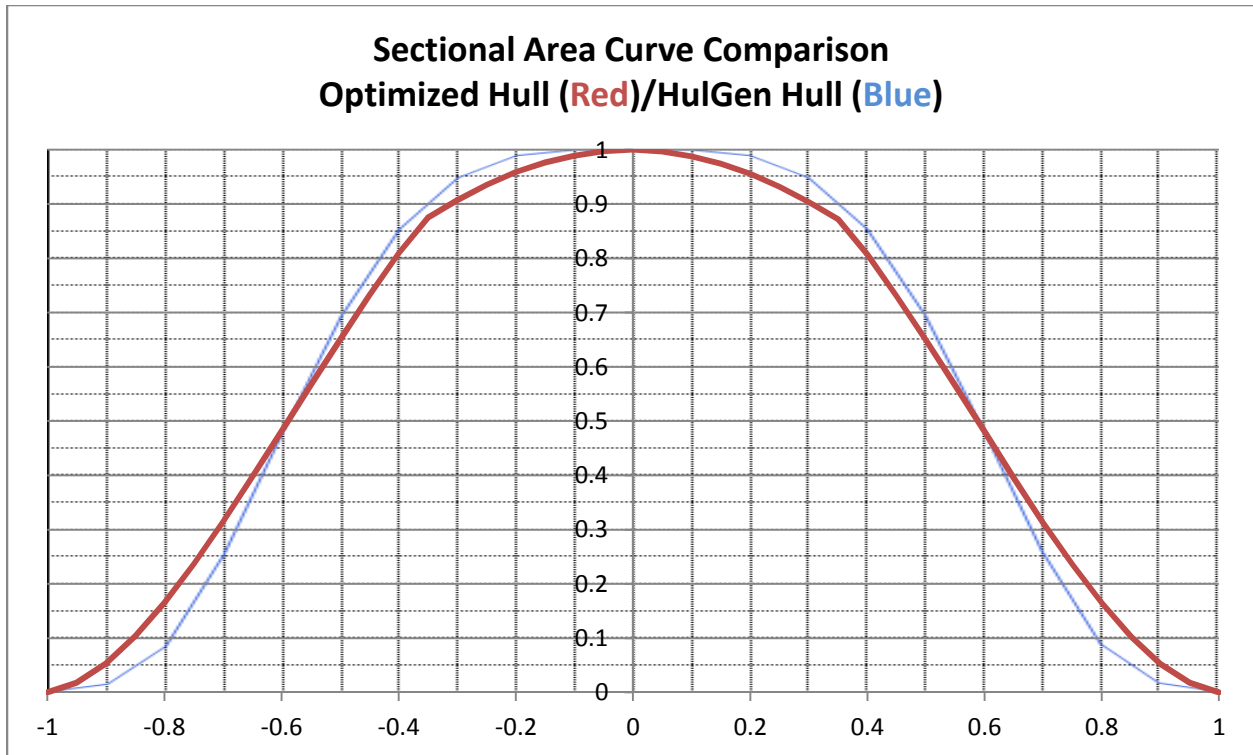


Figure 28: Comparison of Optimized & HulGen Sectional Area Curves

This complication was anticipated, given that the program is intended for use in the conceptual design of a hull. The sidehulls were simply shaped and could easily be drawn fair in Rhino 3D; therefore HulGen was only utilized for the centerhull design.

For comparison purposes, a resistance prediction for the HulGen hullform was completed in Michlet. Despite the inability to be completely accurate in recreating the optimized hullform, a parallel midbody was still easily obtained. Figure 29 displays a comparison for the optimized centerhull and the HulGen centerhull wetted body plan.

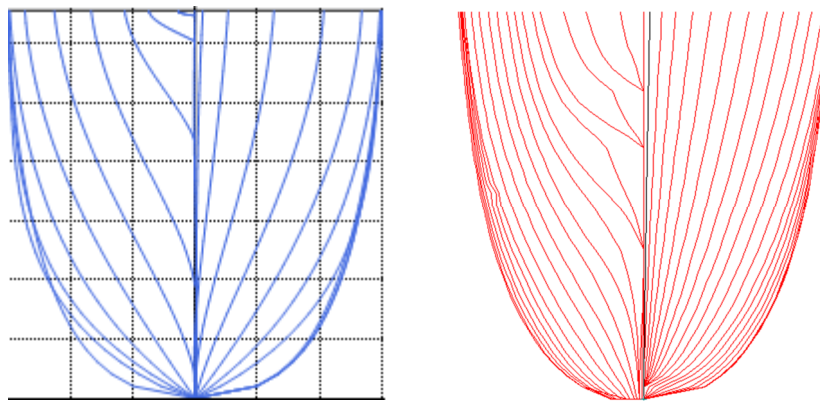


Figure 29: Comparison Of HulGen (Blue) and Optimized (Red) Wetted Body Plans

The major difference in the HulGen hullform was that the total displacement was approximately 3% higher than the desired 95% center hull displacement. A design waterline view of the HulGen hullform can be seen in Figure 30.

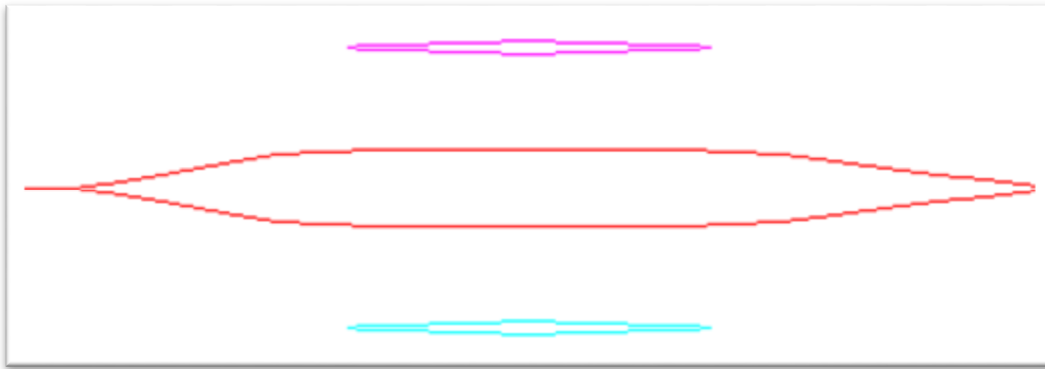


Figure 30: HulGen Hullform Design Waterline

Figure 31 shows a comparison of the predicted residuary resistance of the optimized and HulGen hullforms.

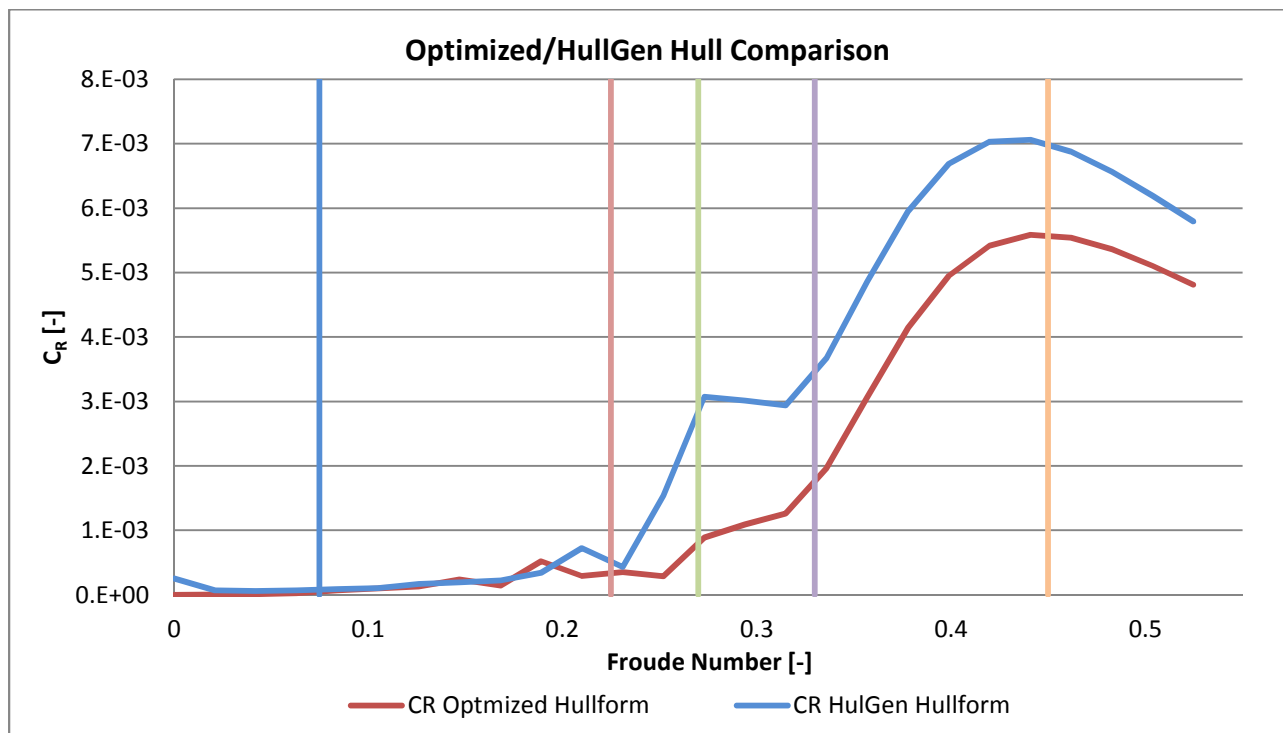


Figure 31: Comparison of Optimized Hullform to the HulGen Hullform

The inability to recreate the optimized hullform curves in HulGen had a significant effect on the predicted residuary resistance at Froude numbers above 0.2. The intent of the model construction for this project was not to necessarily build the “best” trimaran, but to validate a process that utilized

existing hullform design tools. Therefore, the physical model's centerhull was constructed from the geometry created in HulGen.

HulGen exported the centerhull's geometry into Rhino 3D. The sidehulls geometry was not created in HulGen therefore their geometry was imported into Rhino 3D via an offset table. A 3D model was then created for each hull. Figure 32 and 33 show the wetted body plans of the physical model's centerhull and sidehulls respectively.

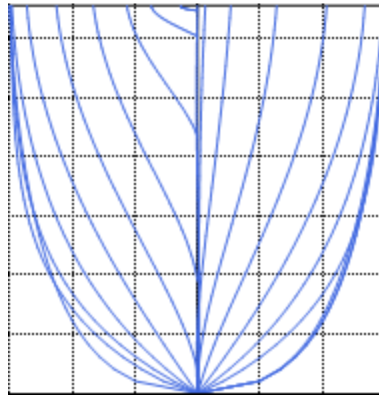


Figure 32: Physical Model Centerhull Wetted Body Plan

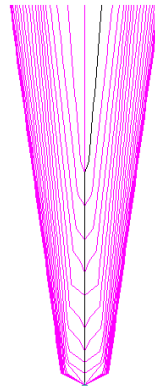


Figure 33: Physical Model Sidehull Wetted Body Plan

RhinoCAM was utilized to create 2 ½ axis tool paths for the construction of the physical model. A 1/52 scale hullform was milled using the University's milling robot and the hull was finished with fiberglass epoxy. For a more detailed description of the hull construction along with more detailed results, see the lab report in Appendix I.

Model Test Data

The completed model was tested in the University of New Orleans NAME towing tank. The model had the capability to change both the longitudinal and transverse positions of the sidehulls. For this report, a single transverse position and three longitudinal positions were tested. Only the longitudinal position at amidships could be compared to the predicted results since, once constructed, the sectional area curve of the center hull could not be changed on the physical model.



Figure 34: Physical Trimaran Model Based on HulGen Hullform

The design and construction of the model's cross-structure proved to be one of the most difficult aspects of the model construction. The cross-structure needed to be light weight and preferably as low to the waterline as possible so the stability of the model was not overly affected. Unfortunately, the underside of the cross-structure interfered with the bow waves at high speeds so the data for those tests could not be used. Figure 35 is a view of the model from the bow looking aft. The bottom of the blue and red stripes on the hulls marks the design waterline.

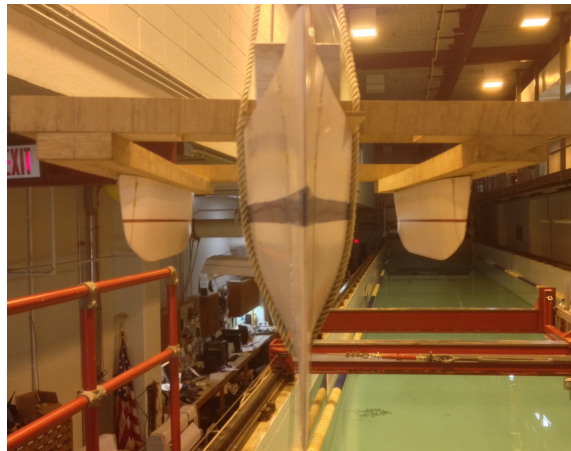


Figure 35: Trimaran Model Looking Aft

A comparison of the test data to the Michlet predictions of the HulGen hullform for the valid Froude number range can be seen in Figure 36.

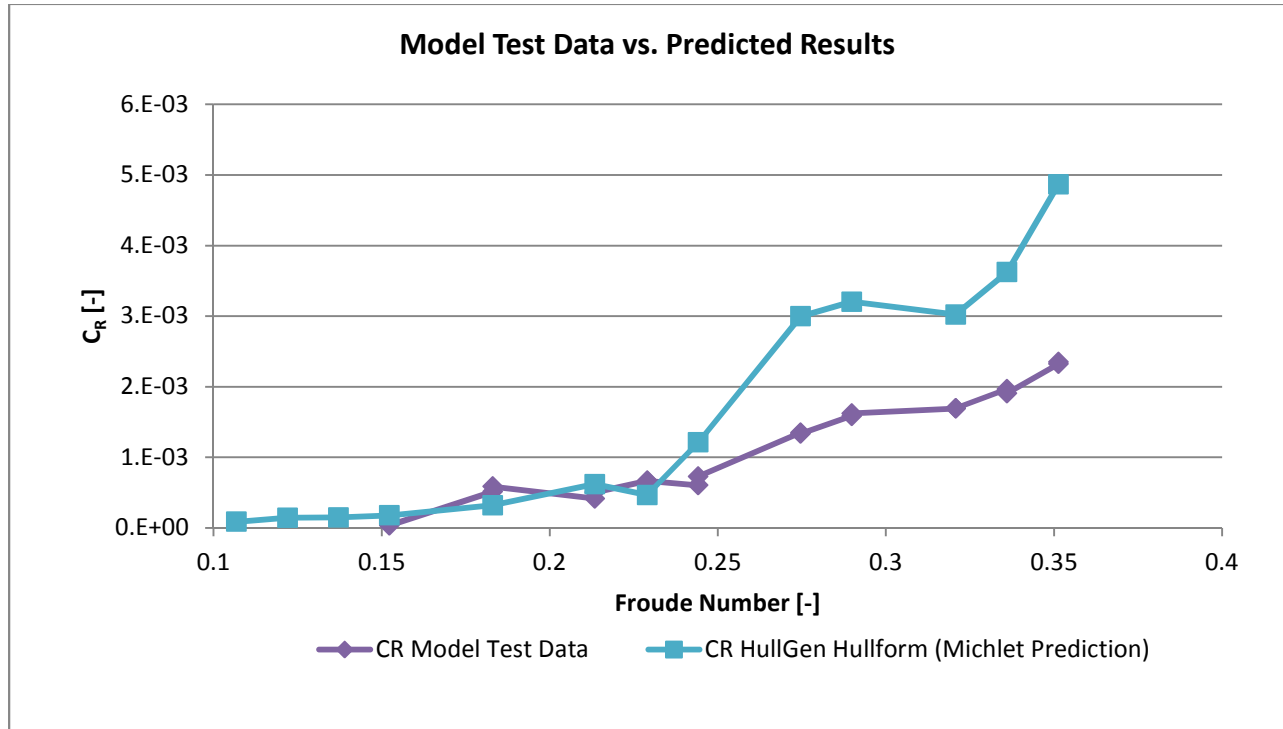


Figure 36: Model Test Data vs. Michlet Predicted Results of HulGen Hullform

At Froude numbers greater than 0.25, the Michlet predictions were significantly higher than the experimental data. This is not consistent with the observed pattern from the tool validation data. See the Future Research section for further information.

Conclusion

Methodology

The “generalized” trimaran design methodology has the capability to advance research in trimaran warship design. Due to the methodology’s ability for rapid reproduction of hullforms, a trimaran hullform database could be easily created; a database that could be used to make critical decisions in the concept design phase.

The methodology has been proven for use in creating new or converting existing hullforms. When converting existing hullforms, the process is more complicated and the ability to minimize the resistance depends on the hullforms original design intent. For example, the pre-Triton hullform has clearly advanced beyond the conceptual design phase, and therefore, is already optimized for its intended mission. Even if this is the case, the methodology can be very beneficial to a ship designer since it allows for design excursions to study the effectiveness of an existing hullform for a new mission. Since there are very few powered trimaran warships constructed, new trimaran hullform designs would benefit from the ability to analyze the benefits and drawbacks of the existing designs.

When creating new hullforms, the methodology has the potential to play a complimentary role to the existing HulGen program. Several aspects of the existing HulGen program would need to be tailored to both the trimaran hullform and the proposed methodology for this to be a seamless hullform design tool.

The Future of the Trimaran Hullform Development for Warships

The typical “rules of thumb” for monohulls cannot be applied to trimaran warships. For example, restricting the length or displacement of a “frigate-sized” or “destroyer-sized” trimaran can be counterproductive to its design. Trimarans achieve a reduction in resistance because of the slenderness of their hullforms. Therefore, it should be reasonable to expect that a trimaran that carries the same payload as a monohull would be longer. Additionally, added structure is needed between the hulls that a monohull does not require, which means it may have a larger displacement. However, with these penalties comes a larger deck area, higher stability, more arrangeable internal hull deck area and, maybe, most importantly, more volume.

The trimaran hullform has the potential to be a valuable asset to a naval fleet. Many aspects of the hullform are well suited to meet naval requirements, i.e. “ilities”, but the world’s navies have very little experience with their design. At the time of this report the US Navy had approximately 280 commissioned ships, only two being trimarans. For the technology to be a viable option, the knowledge must be advanced for the hullform design process. With more research focused on trimaran warship design, the technology has the opportunity to be very beneficial to meet the many unknown, and rapidly changing future missions. The “Generalized” Trimaran Methodology can help in the understanding of how the trimaran hullform can be an integral asset to future naval fleets.

Future Research

Several excursions from this thesis have been identified that could improve and further validate the methodology.

Improvement of Physical Model

Improvement of the physical model construction would help fill out the resistance curve for higher speeds. This was the first experience the author had with constructing a model. Under an accelerated schedule, the learning curve for the process is steep, especially with a three hulled system whose alignment must be very precise. The model could be improved by adding freeboard to the side hulls and constructing a lightweight, yet rigid, cross-structure that would not interfere with the waves between the hulls. The ability to gather results at higher speeds would help with the validation of the resistance tools used in future applications of the methodology.

Resistance Prediction Tool vs. Model Test Data

The model test data did not follow the observed trend from the Michlet validation process which was unfortunate. The methodology would benefit from the use of another resistance prediction tool such as a CFD program. The CFD results could be compared to the Michlet predictions and the model test data. If the model is improved as suggested then a wider range of speeds could be measured for during additional model tests.

Improvement & Additional Validation of Methodology

This thesis was an extension of a previous study in which a hullform was already selected. The methodology was applied to an existing hullform with the goal of changing the geometry to meet a new mission. Designing a new hullform from scratch might prove to create hullforms with improved resistance performance. Also the HulGen program would be of greater use since it would be utilized as it was originally intended. This could also lead to a database of trimarans with varying lengths, displacements and sidehull displacements as well as positions. If such a database existed, much of the time researching important design decisions in the conceptual phase could be eliminated. This work could also help advance the research on the effects of the interference waves between the hulls.

In addition to the hullform database, a sidehull “measures of effectiveness” rating system could be created. While resistance results can be easily compared since they are numerical, other sidehull benefits are not. For example, survivability, mission effectiveness, and the ability to carry out flight deck and small craft operations are not easily quantified numerically. A sidehull location rating system could be developed for the above categories based on sidehull position and size.

Finally, the methodology could expand to include a conceptual level stability analysis process. During the project, a KG was set just to create a baseline for comparison of different transverse sidehull locations. Even though the sidehull transverse location has no effect on the sectional area curve, the use of a trimaran hullform design tool could aid in making conceptual level decisions.

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Appendix I: Trimaran Model Test Lab Report

This report describes the experiments performed at the University of New Orleans Naval Architecture & Marine Engineering facilities during March and April of 2014 to determine the total resistance of a model scale trimaran constructed to validate the predicted results of a Master's thesis. A 1/52nd scale trimaran model was constructed and tested in the facility's tow tank.

Model Design

The model is based on the trimaran hullform developed in the Master's thesis *Development of a Generalized Hullform Design Methodology for a Naval Warship*. The full scale ship's characteristics can be seen in Table 9 while the 1/52nd scale model characteristics can be found in Table 10. The model was designed to be as large as possible without needing to exceed the tank carriage maximum speed. For more information on the design of the hullform, please see the previously mentioned thesis.

| Full Ship | Centerhull | Sidehull (Each) | Total |
|--------------------------|------------|-----------------|--------|
| Length (m) | 120 | 42.865 | 120 |
| Beam (m) | 9.144 | 1.6033 | 35.25 |
| Draft (m) | 9.99744 | 4.5691 | 9.999 |
| Volume (m3) | 5228.672 | 134.255 | 5640.2 |
| Displacement (tonne) | 5364.728 | 137.748 | 5787.0 |
| Block Coefficient, C_B | 0.4766 | 0.428 | [-] |

Table 9: Trimaran Full Ship Characteristics

| Model ($\lambda = 52$) | Centerhull | Sidehull (Each) | Total |
|--------------------------|------------|-----------------|---------|
| Length (m) | 2.3077 | 0.8424 | 2.3077 |
| Beam (m) | 0.1758 | 0.0308 | 0.5351 |
| Draft (m) | 0.1923 | 0.0879 | 0.1923 |
| Volume (m3) | 0.03719 | 0.000955 | 0.03910 |
| Displacement (tonne) | 0.03713 | 0.00095 | 0.03903 |
| Block Coefficient, C_B | 0.4766 | 0.428 | [-] |

Table 10: Trimaran Model Characteristics ($\lambda = 52$)

Test Description

The tests were performed on 8 & 12 of April 2014 at the University of New Orleans tow tank facility and followed the ITTC – Recommended Procedures and Guidelines for Resistance Tests. The model was tested without appendages to determine the resistance coefficients of the basic form.

The model was attached to the carriage using a force balance rod which was placed along the propeller shaft line and was connected to the model at the Longitudinal Center of Buoyancy (LCB). The rod is free to move vertically to allow the model to heave and pitch as needed.

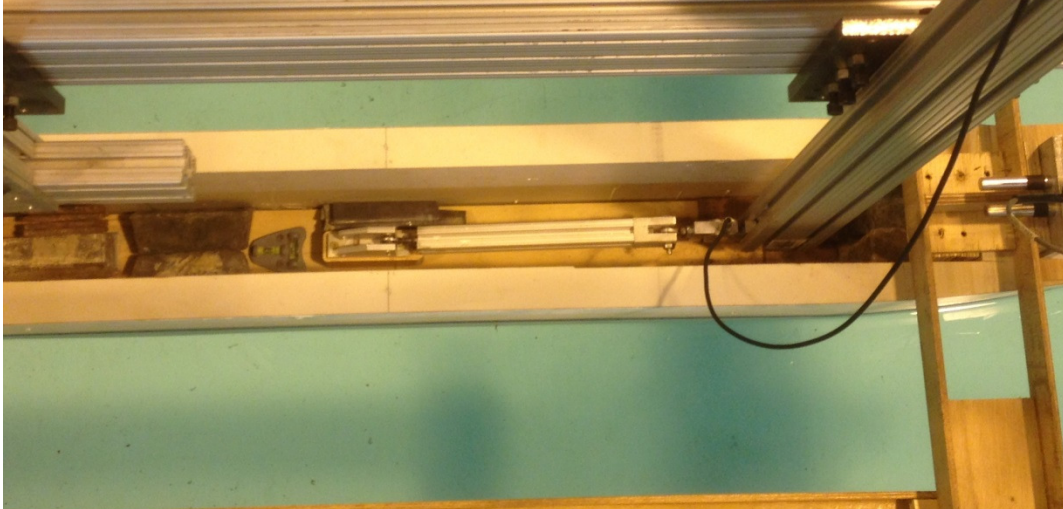


Figure 37: Model Force Balance Rod

Additional yaw limiting rods attached to the carriage were placed in the limiting tracks fore and aft of the model. This limited the yaw motion of the model and ensured the model followed a straight towing line through the tank. Potentiometers were attached to the fore and aft limiting tracks to measure the heave of the bow and stern during the test runs.

The load cell and potentiometers were calibrated prior to each test day and were zeroed when the model was connected to the carriage. The calibration was periodically checked during the testing process.

The model was equipped with a wooden cross-structure so the side hulls could be aligned properly. Holes were drilled to mark the possible longitudinal and transverse locations. The test results of concern are those with the sidehulls centered at amidships, therefore this data will be presented in this report.

First the model was weighed using a crane scale. Prior to lifting the model, the scale was zeroed with the lifting attachments. Once a model weight was determined, the model was ballasted based on the scaled displacement at the measured tank water properties and was set to an initial zero trim condition.

The experiment included 16 speeds at which the model would be tested and each speed was tested twice to ensure accuracy. Due to some wave interference with the cross-structure at high speeds, only 13 of the speed results were valid. High and low speeds were alternated so the water turbulence could remain as close to constant for each test as possible. A turbulence run was performed prior to a set of tests if an extended amount of time had passed after the last test run.

Water Properties

Measurements were taken of the temperature and the density of the water in the tow tank. The weight density is a function of the water temperature and is also found using the tables in ITTC-Recommended Procedures 7.5-02-01-03. The kinematic viscosity was taken from this table as well. Table 11 shows the properties of the tank water measured for both testing dates.

| Tow Tank Fresh Water Properties | | |
|---------------------------------|----------|-------------------|
| Temperature, T | 19 | °C |
| Density, ρ | 998.4083 | kg/m ³ |
| Viscosity, ν | 1.03E-06 | m ² /s |

Table 11: Tank Water Properties

Results

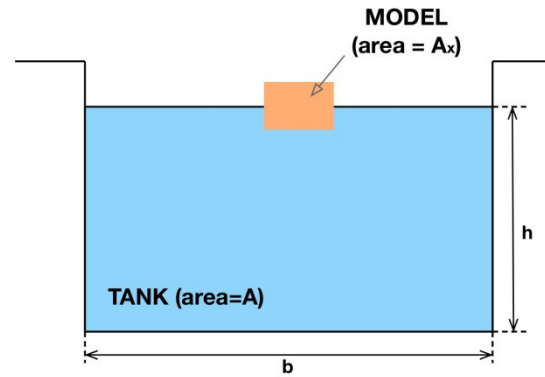
The total model coefficient, C_{TM} , was calculated from the measured resistance. The residual resistance, C_R , was found by subtracting the 1957 ITTC friction coefficient value, C_{FM} , from C_{TM} . The speed of the model, V_M , was calculated from the carriage speed, V_C , using the blockage coefficient.

$$\frac{V_M}{\left(1 + \frac{\Delta V}{V_C}\right)} = V_C$$

$$\frac{\Delta V}{V_C} = 0.67 \frac{A_x}{A} \left(\frac{L_{WLM}}{B_M}\right)^{3/4} \left(\frac{1}{1 - Fr_n^2}\right)$$

$$A_x = C_x(T \times B)$$

$$Fr_n = \frac{V_C}{\sqrt{gh}}$$



$$C_R = C_{TM} - C_{FM}$$

Sinkage, Z_V , and trim, α , of the model was measured and calculated as follows, where L_{ZV} is the length between the potentiometers.

$$\tan \alpha = \frac{Z_{VF} - Z_{VA}}{L_{ZV}}$$

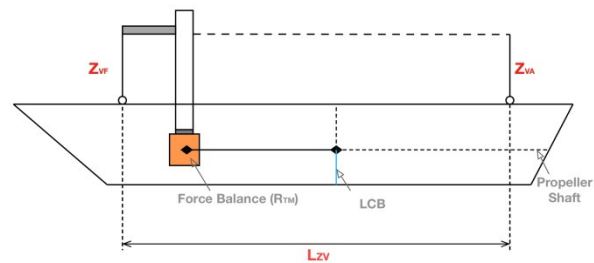


Table 12 shows the results of each test run for speeds where the bow waves did not interact with the cross-structure. While Table 13 gives the sinkage and trim data.

| RPM | Carriage Speed, V_C | V_M | Fr | $R_{T,M}$ | $C_{F-ITTC,M}$ | $C_{T,M}$ | C_R |
|---------|--------------------------|---------|---------|-----------|----------------|-----------|----------|
| rev/min | m/s | m/s | [-] | N | [-] | [-] | [-] |
| 275 | 0.49893 | 0.50773 | 0.10680 | 0.52798 | 0.00456 | 0.00364 | -0.00092 |
| 275 | 0.49893 | 0.50773 | 0.10680 | 0.60951 | 0.00456 | 0.00420 | -0.00036 |
| 314 | 0.56969 | 0.57978 | 0.12196 | 0.75094 | 0.00443 | 0.00397 | -0.00047 |
| 314 | 0.56969 | 0.57978 | 0.12196 | 0.73143 | 0.00443 | 0.00386 | -0.00057 |
| 353 | 0.64044 | 0.65184 | 0.13712 | 1.00305 | 0.00432 | 0.00419 | -0.00013 |
| 353 | 0.64044 | 0.65184 | 0.13712 | 0.97211 | 0.00432 | 0.00406 | -0.00026 |
| 392 | 0.71120 | 0.72393 | 0.15228 | 1.22658 | 0.00423 | 0.00415 | -0.00008 |
| 392 | 0.71120 | 0.72393 | 0.15228 | 1.25906 | 0.00423 | 0.00426 | 0.00003 |
| 471 | 0.85453 | 0.87003 | 0.18301 | 1.95535 | 0.00407 | 0.00459 | 0.00051 |
| 471 | 0.85453 | 0.87003 | 0.18301 | 1.98710 | 0.00407 | 0.00466 | 0.00059 |
| 549 | 0.99604 | 1.01439 | 0.21338 | 2.53083 | 0.00395 | 0.00437 | 0.00042 |
| 549 | 0.99604 | 1.01439 | 0.21338 | 2.58219 | 0.00395 | 0.00445 | 0.00050 |
| 589 | 1.06861 | 1.08848 | 0.22896 | 3.04410 | 0.00390 | 0.00456 | 0.00067 |
| 589 | 1.06861 | 1.08848 | 0.22896 | 3.04295 | 0.00390 | 0.00456 | 0.00066 |
| 628 | 1.13937 | 1.16075 | 0.24417 | 3.37743 | 0.00385 | 0.00445 | 0.00060 |
| 628 | 1.13937 | 1.16075 | 0.24417 | 3.47249 | 0.00385 | 0.00457 | 0.00073 |
| 706 | 1.28089 | 1.30543 | 0.27460 | 4.90381 | 0.00376 | 0.00511 | 0.00135 |
| 706 | 1.28089 | 1.30543 | 0.27460 | 4.88860 | 0.00376 | 0.00509 | 0.00133 |
| 745 | 1.35164 | 1.37785 | 0.28984 | 5.67251 | 0.00372 | 0.00530 | 0.00158 |
| 745 | 1.35164 | 1.37785 | 0.28984 | 5.71272 | 0.00372 | 0.00534 | 0.00162 |
| 824 | 1.49497 | 1.52472 | 0.32073 | 6.99363 | 0.00365 | 0.00534 | 0.00169 |
| 824 | 1.49497 | 1.52472 | 0.32073 | 6.99647 | 0.00365 | 0.00534 | 0.00169 |
| 863 | 1.56573 | 1.59732 | 0.33600 | 8.02246 | 0.00362 | 0.00558 | 0.00197 |
| 863 | 1.56573 | 1.59732 | 0.33600 | 7.93736 | 0.00362 | 0.00552 | 0.00191 |
| 902 | 1.63649 | 1.67001 | 0.35129 | 9.28108 | 0.00359 | 0.00591 | 0.00232 |
| 902 | 1.63649 | 1.67001 | 0.35129 | 9.32823 | 0.00359 | 0.00594 | 0.00235 |

Table 12: Test Results - Resistance Coefficients

| RPM | Fr | Fwd Heave | Aft Heave | Sinkage | Trim (+ Bow Down) | |
|---------|--------|-----------|-----------|---------|-------------------|--------|
| rev/min | [-] | in | in | in | rad | deg |
| 275 | 0.1068 | -0.0348 | -0.0149 | -0.0248 | 0.0004 | 0.0207 |
| 275 | 0.1068 | -0.0252 | -0.0091 | -0.0172 | 0.0003 | 0.0168 |
| 314 | 0.1220 | -0.0364 | -0.0111 | -0.0238 | 0.0005 | 0.0264 |
| 314 | 0.1220 | -0.0502 | -0.0227 | -0.0365 | 0.0005 | 0.0287 |
| 353 | 0.1371 | -0.0521 | -0.0237 | -0.0379 | 0.0005 | 0.0296 |
| 353 | 0.1371 | -0.0636 | -0.0312 | -0.0474 | 0.0006 | 0.0338 |
| 392 | 0.1523 | -0.0647 | -0.0312 | -0.0479 | 0.0006 | 0.0350 |
| 392 | 0.1523 | -0.0765 | -0.0405 | -0.0585 | 0.0007 | 0.0376 |
| 471 | 0.1830 | -0.0960 | -0.0497 | -0.0728 | 0.0008 | 0.0483 |
| 471 | 0.1830 | -0.1078 | -0.0584 | -0.0831 | 0.0009 | 0.0516 |
| 549 | 0.2134 | -0.1345 | -0.0726 | -0.1035 | 0.0011 | 0.0646 |
| 549 | 0.2134 | -0.1455 | -0.0805 | -0.1130 | 0.0012 | 0.0679 |
| 589 | 0.2290 | -0.1692 | -0.0979 | -0.1335 | 0.0013 | 0.0745 |
| 589 | 0.2290 | -0.1696 | -0.0978 | -0.1337 | 0.0013 | 0.0750 |
| 628 | 0.2442 | -0.1790 | -0.0993 | -0.1391 | 0.0015 | 0.0832 |
| 628 | 0.2442 | -0.1936 | -0.1069 | -0.1502 | 0.0016 | 0.0905 |
| 706 | 0.2746 | -0.2591 | -0.1219 | -0.1905 | 0.0025 | 0.1433 |
| 706 | 0.2746 | -0.2599 | -0.1197 | -0.1898 | 0.0026 | 0.1464 |
| 745 | 0.2898 | -0.2754 | -0.1405 | -0.2079 | 0.0025 | 0.1409 |
| 745 | 0.2898 | -0.2935 | -0.1480 | -0.2207 | 0.0027 | 0.1520 |
| 824 | 0.3207 | -0.3408 | -0.2497 | -0.2952 | 0.0017 | 0.0951 |
| 824 | 0.3207 | -0.3573 | -0.2588 | -0.3080 | 0.0018 | 0.1028 |
| 863 | 0.3360 | -0.3869 | -0.3210 | -0.3539 | 0.0012 | 0.0688 |
| 863 | 0.3360 | -0.3881 | -0.3202 | -0.3542 | 0.0012 | 0.0709 |
| 902 | 0.3513 | -0.3932 | -0.3894 | -0.3913 | 0.0001 | 0.0040 |
| 902 | 0.3513 | -0.4017 | -0.3972 | -0.3994 | 0.0001 | 0.0047 |

Table 13: Test Results - Sinkage & Trim

At low speeds, the residuary resistance is calculated to be negative. This is common in many experimental results because the forces at these speeds are so small that they cannot accurately be measured. Therefore the speeds with negative values were not used in the analysis. For an analysis of the results, see the Results section of the Master's thesis.

Model Construction

The centerhull of the model is primarily constructed from high density foam while the side hulls are of Monterey Pine. The hulls were shaped through a 2 ½ axis milling process using the University of New Orleans milling robot. Each hull was first modeled in Rhino 3D and the toll paths were then created using RhinoCAM.

First the centerhull centerline buttock was cut from aluminum to create a rigid spine for the model. Next the port and starboard halves of the centerhull were milled from 4" sheets of high density foam. Multiple cuts were required to get remove enough material so the hull could be faired.



Figure 38: Centerhull Rough Cut – Starboard

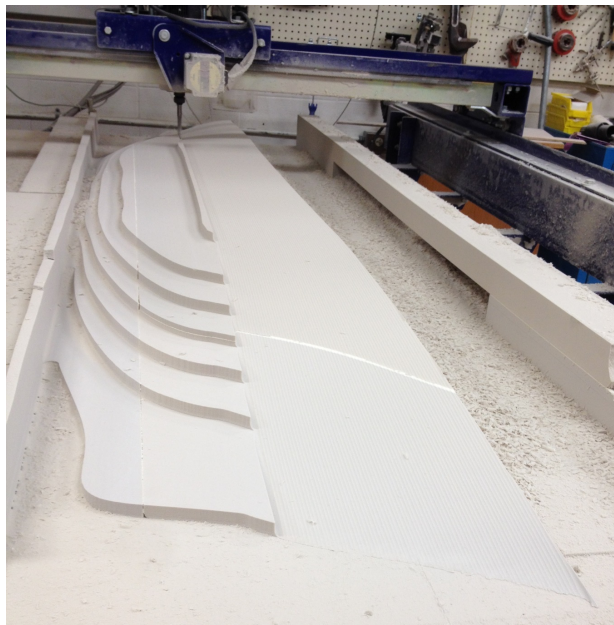


Figure 39: Centerhull during Smoothing Cut – Starboard

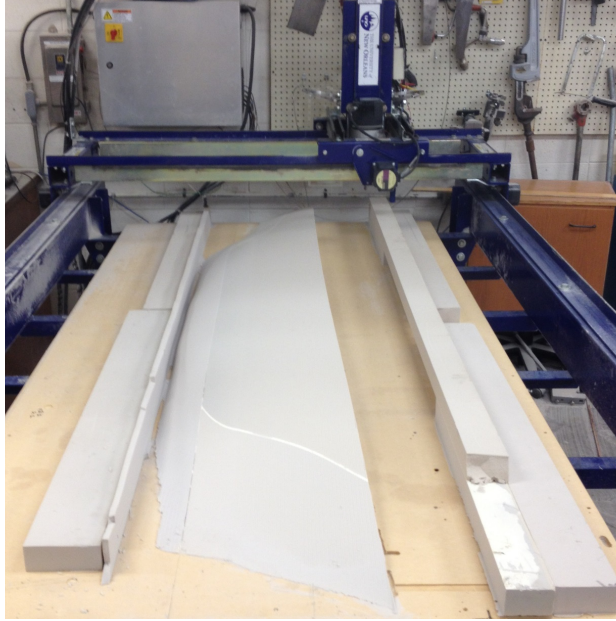


Figure 40: Center Hull Post Smoothing Cut - Starboard

The side hulls were created using the same process.

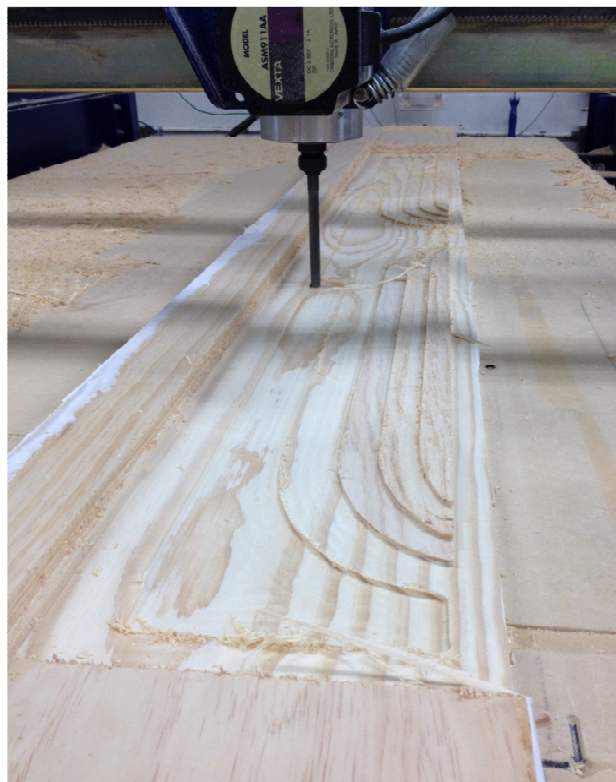


Figure 41: Side Hull Rough Cut – Starboard



Figure 42: Side Hull Smooth Cut – Starboard

Once the halves were sanded smooth so the lines created by the tools were removed, they were epoxied to protect the hull from water intrusion. The centerhull was epoxied with fiberglass for added strength.

The halves of each hull were then glued together using marine epoxy. The port and starboard halves of the centerhull were glued to the aluminum center buttock. A hollow rectangular prism was constructed into the centerhull so the testing equipment and ballast could be installed.



Figure 43: Epoxied Centerhull



Figure 44: Epoxied Sidehulls

Marine filling compound was added where needed and sanded. This process was repeated until the hulls were fair. The three hulls were then coated with two coats of marine primer and then the hulls were painted.



Figure 45: Painted Trimaran Hulls

A carriage was constructed so that the centerhull could be leveled and a waterline was added to each hull.



Figure 46: Centerhull Carriage

Finally the cross-structure was added to the hull and the trimaran was assembled. This proved to be one of the most difficult aspects of the project. The three hulls need to be aligned properly so the test data is as accurate as possible. The cross-structure also needed to be rigid so the hulls did not move during the tests but light enough to maintain the vessels stability. The constructed cross-structure was successful in both those aspects but interfered with the bow waves of the three hulls at high speeds. Therefore the model could be improved by creating sidehulls with larger freeboard.

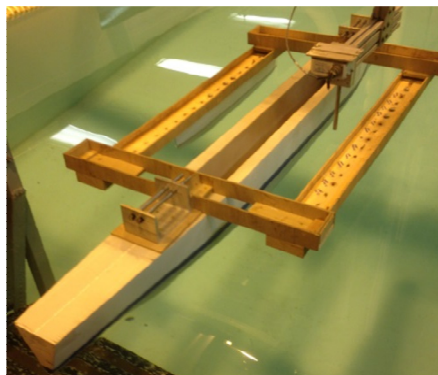


Figure 47: Completed Trimaran Model

Appendix II: Sidehull Length Calculation Program

The program below is written for the 4th order polynomial example.

Quartic Program

```
% This program is the beginning of 3 programs that defines the 4 order
% polynomial sectional area curve of the total side hull SA based on a
% specific displacement.

close all
clear all

syms x dx

%% The code below can be used to create a curve in excel at specific
% intervals.

%t = 0:6:120;
%a = 5.1029155636E-12;
%b = - 1.2831402454E-06;
%c = 8.0482236073E-02;
%d = 1.3921703305E+01;
%funt = a*t.^4+b*t.^3+c*t.^2+d*t;

%a1 = 5.0e-12;
%b1 = - 1.3E-06;
%c1 = 8.25E-02;
%d1 = 4.5E+01;
%funt1 = a1*t.^4+b1*t.^3+c1*t.^2+d1*t

%plot(t,funt,'-',t,funt1,':')
%grid on

%% Use this section to analyze the continuous 4th order Sectional Area
% function

% function in format: a*x^4+b*x^3+c*x^2+d*x+e where e should be 0

K = 1.04395850363546; % not necessary for all equations, set to 1 if not
needed
a = K*(5.648747E-06); % x^4 constant
b = K*(-1.355699E-03); % x^3 constant
c = K*(7.978125E-02);
d = K*(1.872850E-01);
%e = 0;

% Define Sectional Area Curve

SA = a*x^4+b*x^3+c*x^2+d*x;

% Check Volume of curve
```

```

QuatricVol = int(SA,0,120);

%% Solve for Side Hull length from midpoint in terms of dx

%Enter Midpoint
m = 60;

A11 = a*(m-dx)^4+b*(m-dx)^3+c*(m-dx)^2+d*(m-dx);
A12 = a*(m+dx)^4+b*(m+dx)^3+c*(m+dx)^2+d*(m+dx);

DXEQ1 = int(SA, m-dx, m+dx) - 2*dx*A11;
DXEQ2 = int(SA, m-dx, m+dx) - 2*dx*A12;

expand(DXEQ1)
expand(DXEQ2)

%Use SH_dx_solver.m to finish, the expansion on DXEQ1 or DXEQ2 will be needed

```

Side Hull Length Solver

```

%Intended to be run after Quartic.m

%Enter Constants from DXEQ1 output

C11 = -3481008315350011/368934881474191032320; % x^5 constant
C21 = 10784275797/18446744073709551616; % x^4
C31 = 813281422796201455/13835058055282163712; % x^3
C41 = 7722311776309/1152921504606846976; % x^2
C51 = 0; % x

%Enter Constants from DXEQ2 output

C12 = -3481008315350011/368934881474191032320; % x^5 constant
C22 = -10784275797/18446744073709551616; % x^4
C32 = 813281422796201455/13835058055282163712; % x^3
C42 = -7722311776309/1152921504606846976; % x^2
C52 = 0; % x

% Enter desired total ship displacement

disp = 5500; %tonnes

% Enter density of water @ correct temp (C)

rho = 1026.021; %kg/m3

% Calc total volume

```



```

TotVol = disp*1000/rho;

% Calc Side Hull (2) volume at 5%, 10%, 15%, 20%, 30%

vol5 = TotVol*0.05;
vol10 = TotVol*0.1;
vol12 = TotVol*2.374853007*0.05;
vol15 = TotVol*0.15;
vol20 = TotVol*0.20;
vol24 = TotVol*2.374853007*0.1;
vol30 = TotVol*0.30;

% Calc roots of the polynomial DXEQ1 or DXEQ2 (will be the same)
% There will be 5 roots. Chose the REAL root that is makes engineering
sense.
% i.e. small than the total length of the ship
% This will be dx or L/2 of the side hull.

% Enter vol5, vol10, or vol15 based on the SH disp required

DXROOTS1 = roots([C11 C21 C31 C41 C51 -vol24])
DXROOTS2 = roots([C12 C22 C32 C42 C52 -vol24])

% The root that matters (dx) should be equal in both cases.

% Next use to verify your results are correct &
% calc the y intercept of the 4th order SH equation.

```

Y-Intercept Calculator for 4th Order Polynomial

```

% This program verify's the SH_dx_solver results & calculates the
%   y intercept of the 4th order polynomial that represents the total
%   side hull displacement.

%% Verify results

% Enter dx from root calculation in SH_dx_solver

DX = 29.284081888605215;

AA = a*(m-DX)^4+b*(m-DX)^3+c*(m-DX)^2+d*(m-DX);

SHTotVol = int(SA, 60-DX, 60+DX) - 2*DX*AA
% This value should equal the desired volXX
vol5
vol10
vol12
vol15
vol20
vol30

DX

```

```
%% SH 4th order Poly Y Intercept
% If the two volumes are equal (or extremely close)
% Then AA is the yint for the SH 4th order polynomial

SHyint = AA
```

Vita

The author was born in Baltimore, Maryland. He obtained his Bachelor's degree in Mechanical Engineering from the University of Maryland, College Park in 2007, and his professional engineering license in the State of Maryland in 2012. In the fall of 2012 he joined the University of New Orleans engineering graduate program to obtain a Master's degree in Naval Architecture & Marine Engineering.